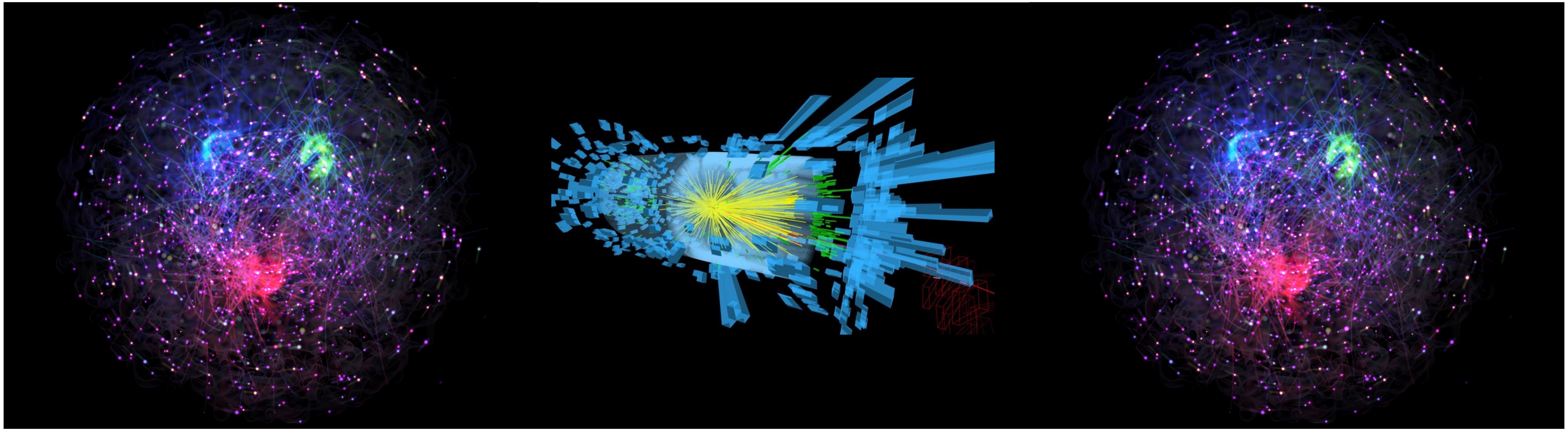
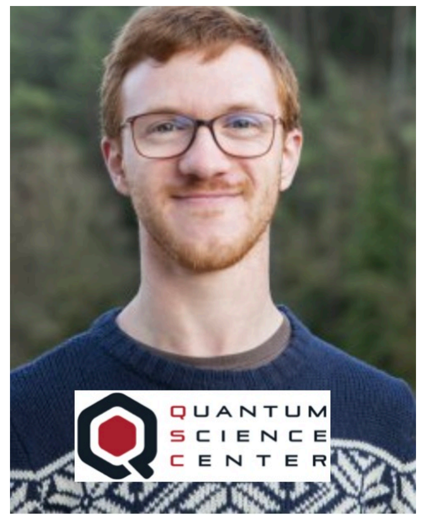
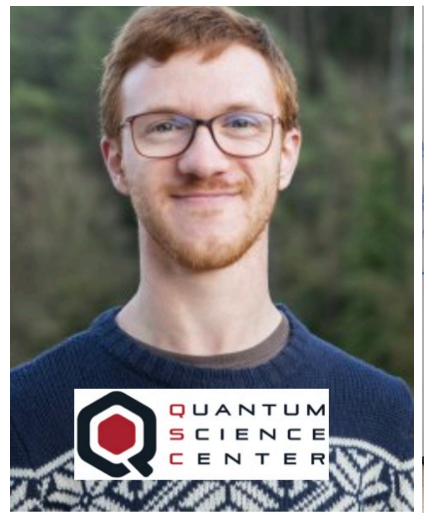
Quantum Simulations of Energy-Loss and Hadronization

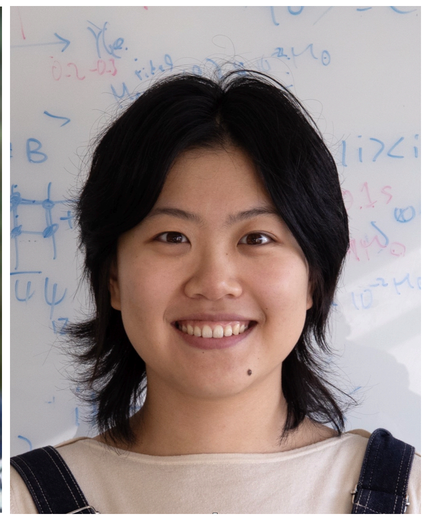




Abelian
Roland Farrell
Marc Illa

Non-Abelian
Marc Illa
Zhiyao Li





Martin Savage
InQubator for Quantum Simulation (IQuS)
University of Washington

IQuS℠

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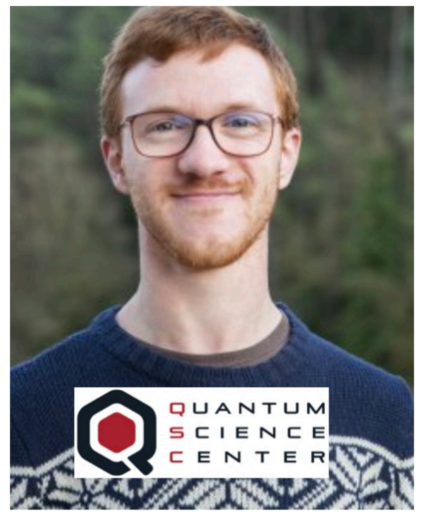
Vacuum and Wavepacket Preparation and Evolution of U(1) Theory in 1+1D

Roland Farrell



Marc Illa

Anthony Ciavarella

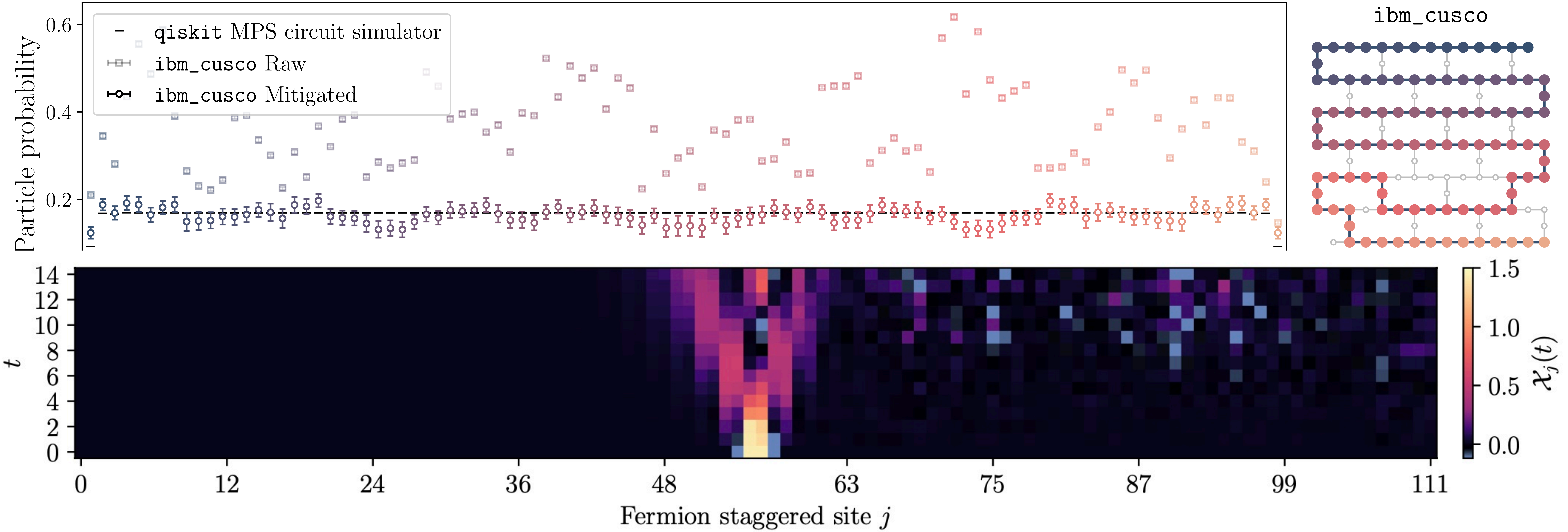
Scalable Circuits for Preparing Ground States on Digital Quantum Computers: The Schwinger Model Vacuum on 100 Qubits

Roland C. Farrell, Marc Illa, Anthony N. Ciavarella, and Martin J. Savage
PRX Quantum **5**, 020315 – Published 18 April 2024

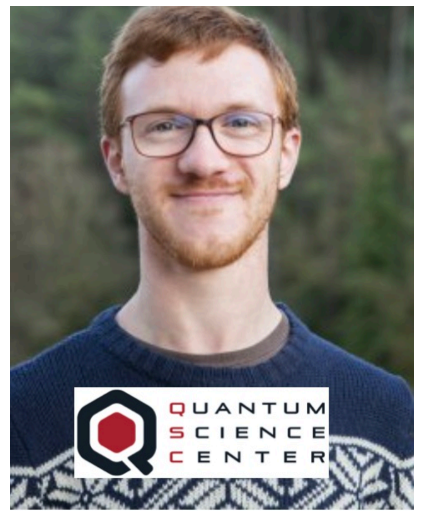
Quantum simulations of hadron dynamics in the Schwinger model using 112 qubits

Roland C. Farrell, Marc Illa, Anthony N. Ciavarella, and Martin J. Savage
Phys. Rev. D **109**, 114510 – Published 10 June 2024

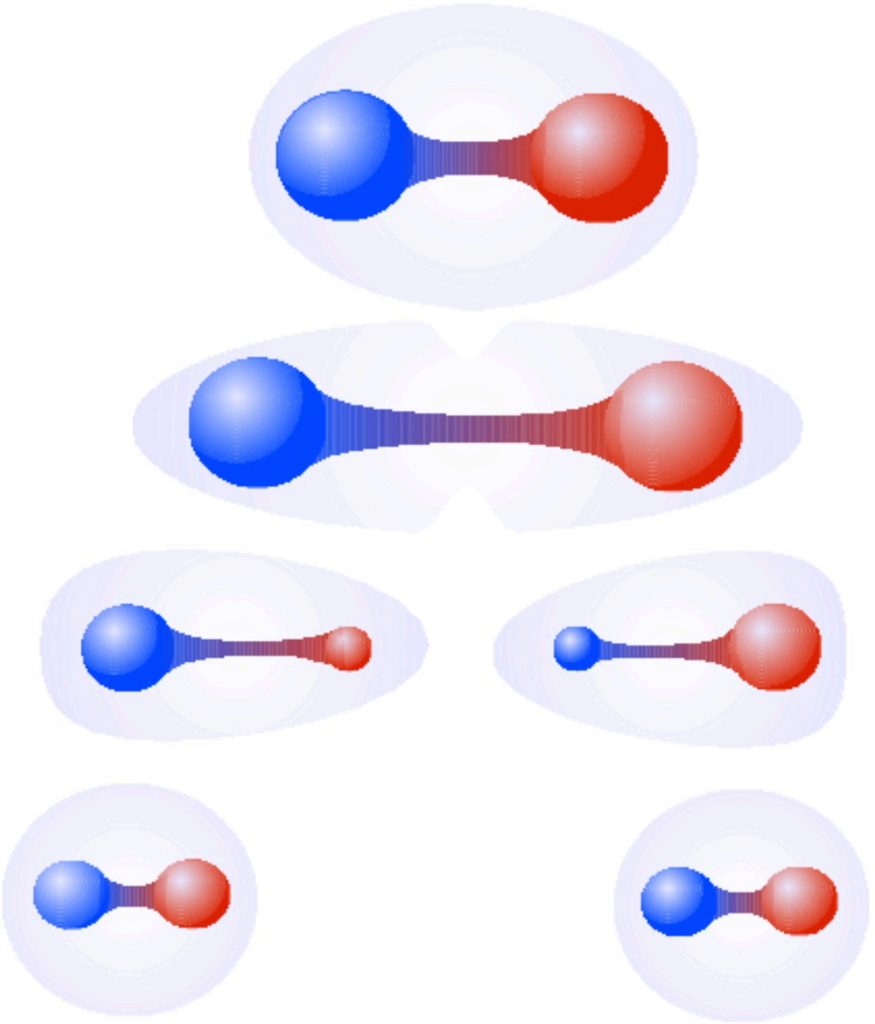
Beams/Pulses of Hadrons

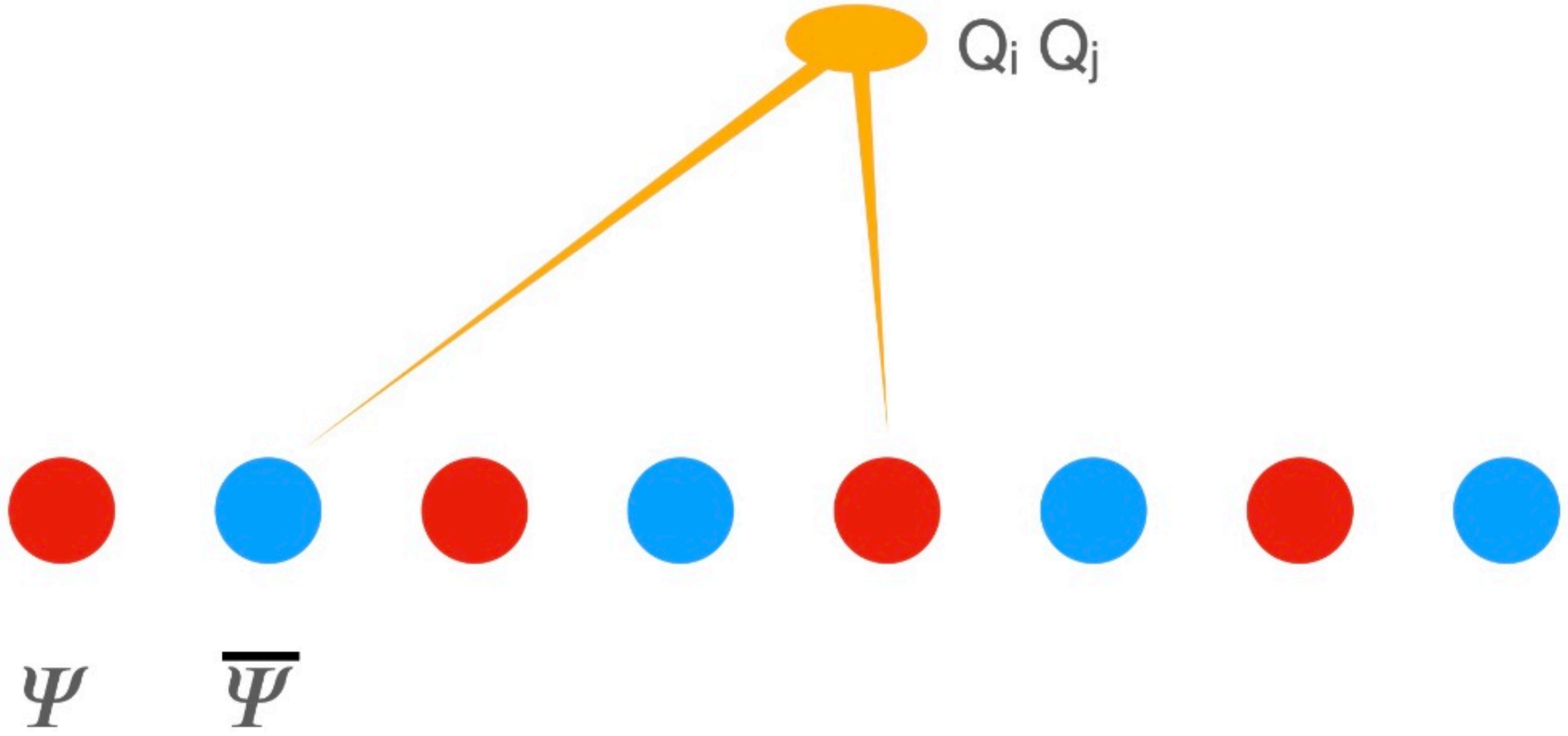


Vacuum and Wavepacket Preparation and Evolution of U(1) Theory in 1+1D



Roland Farrell **Marc Illa** **Anthony Ciavarella**

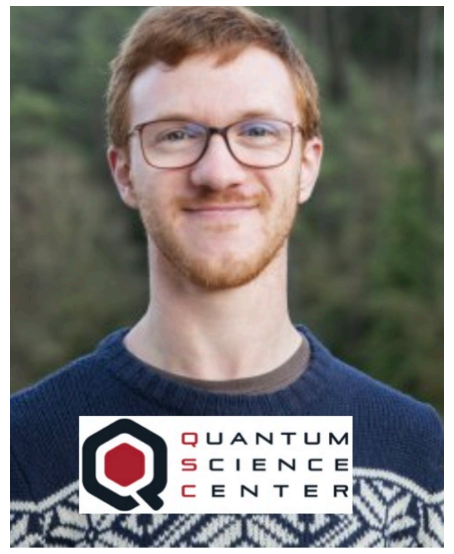




Classical **IBM's Torino**

Systematics in Evolving Two Wavepackets?

Not results from quantum hardware, but two single wavepacket images combined



Lorentz Violation by Lattice Spacing

Steps toward quantum simulations of hadronization and energy loss in dense matter

Roland C. Farrell[1,2,*], Marc Illa[1,†], and Martin J. Savage[1,‡,§]

Show more

Phys. Rev. C **111**, 015202 – **Published 14 January, 2025**

DOI: https://doi.org/10.1103/PhysRevC.111.015202

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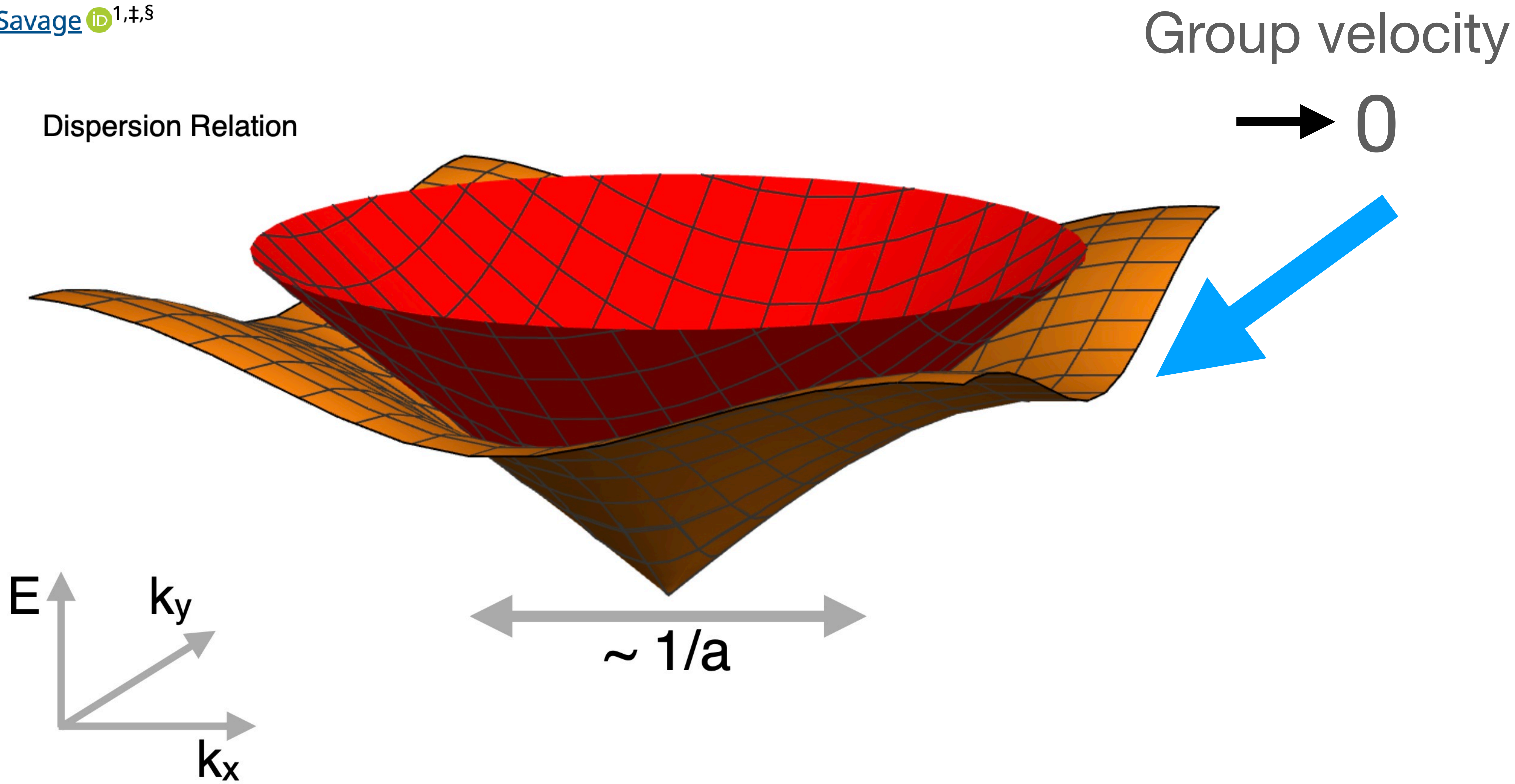
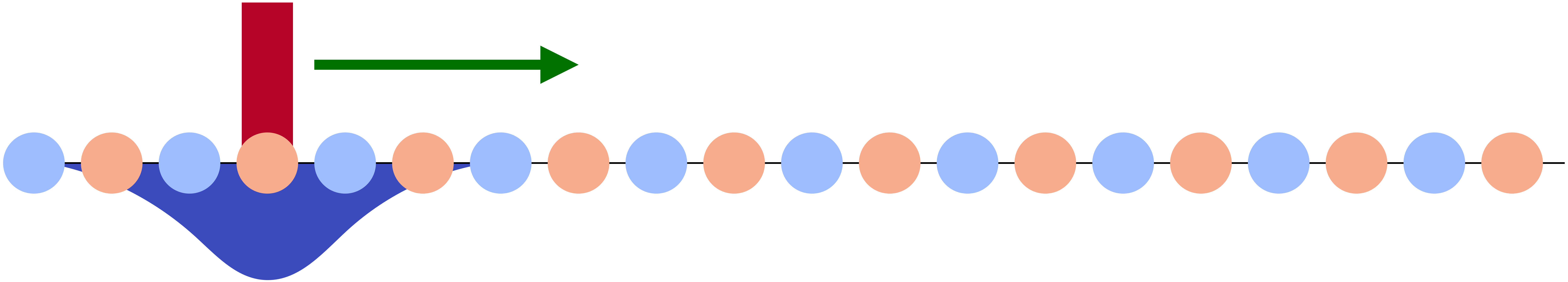


Moving in the Lattice Vacuum

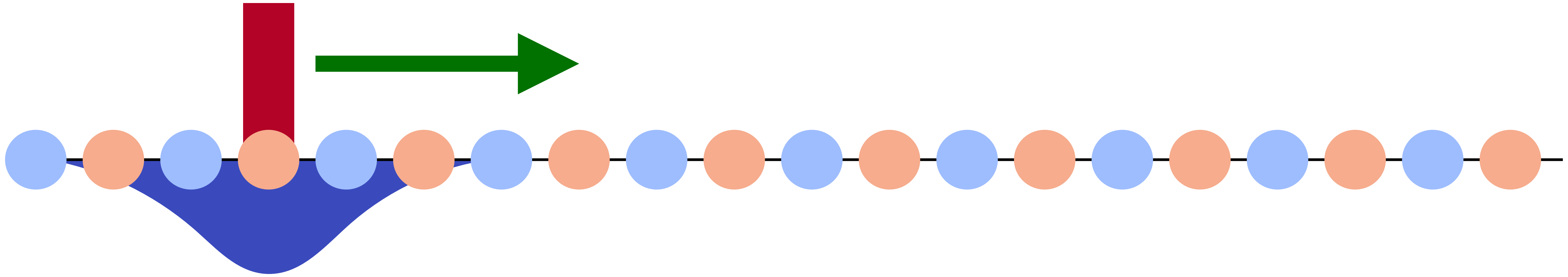
Heavy Quark : constant speed, well-defined position - implemented via Gauss's law



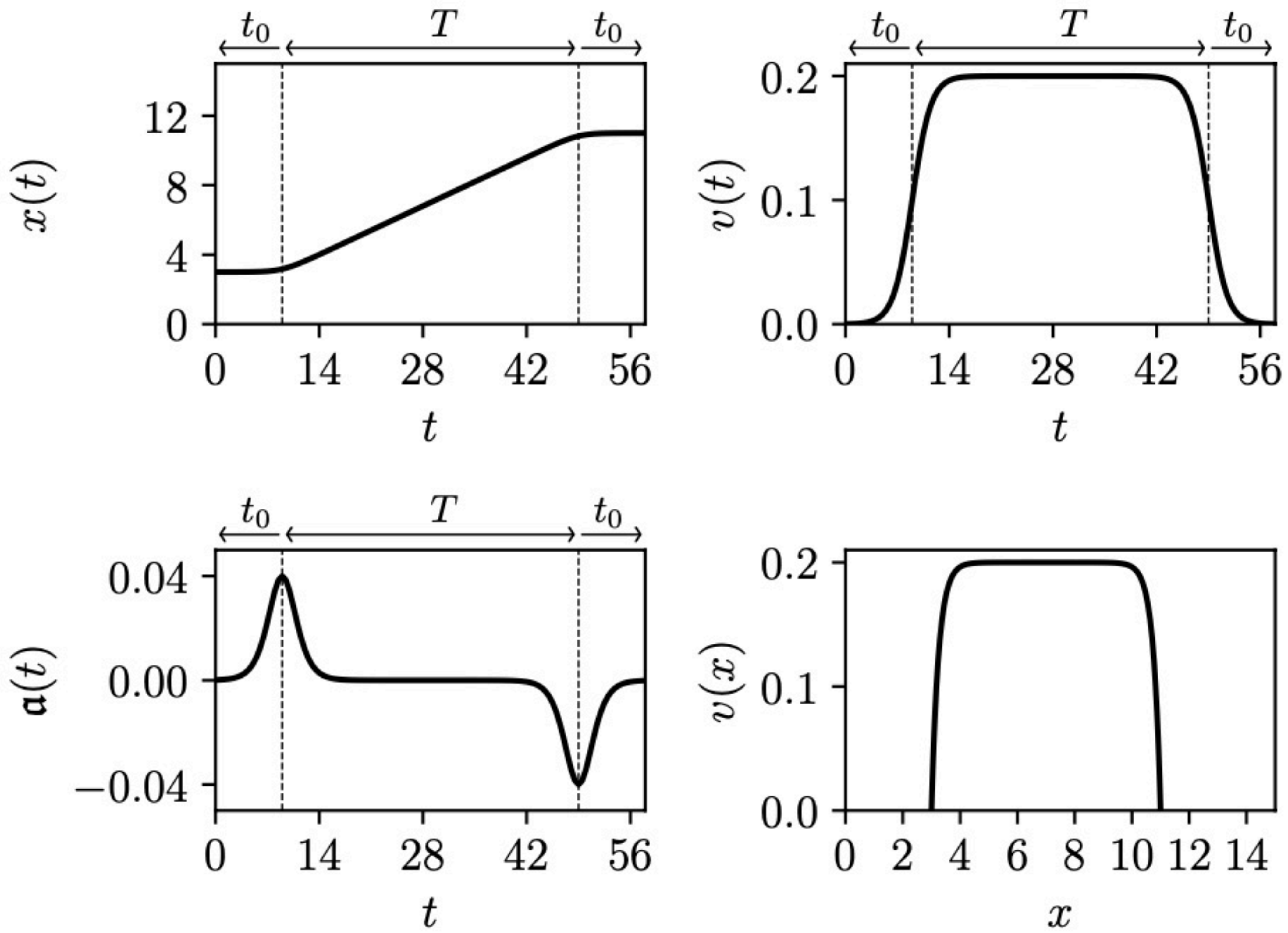
No energy-loss or hadronization in a Lorentz Invariant system

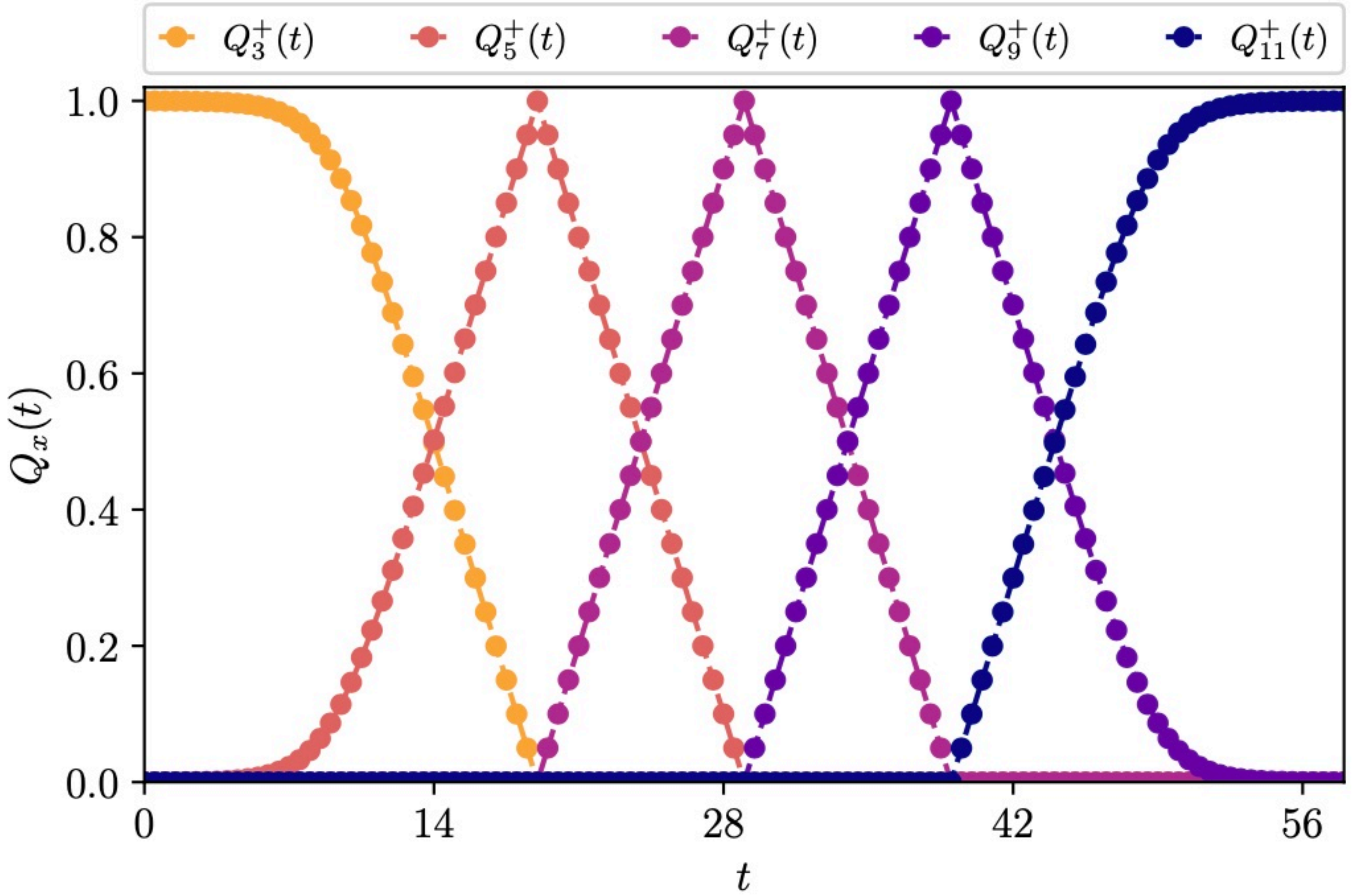
Heavy quarks provide control for parton collisions

Moving in the Lattice Vacuum via Gauss's Law

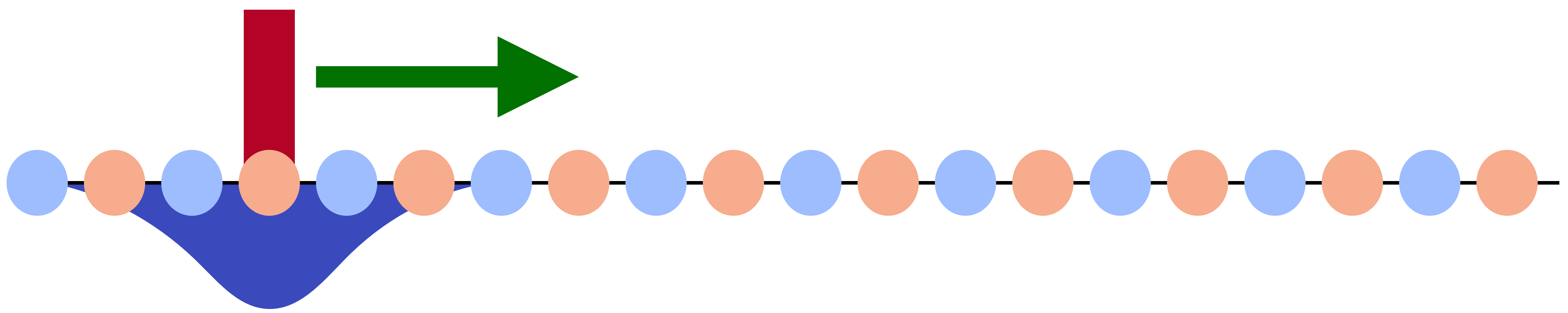


$$Q_{q1} = \frac{Q}{2}\left(x_{q2} - x(t)\right) \;, \quad Q_{q2} = \frac{Q}{2}\left(x(t) - x_{q1}\right)$$



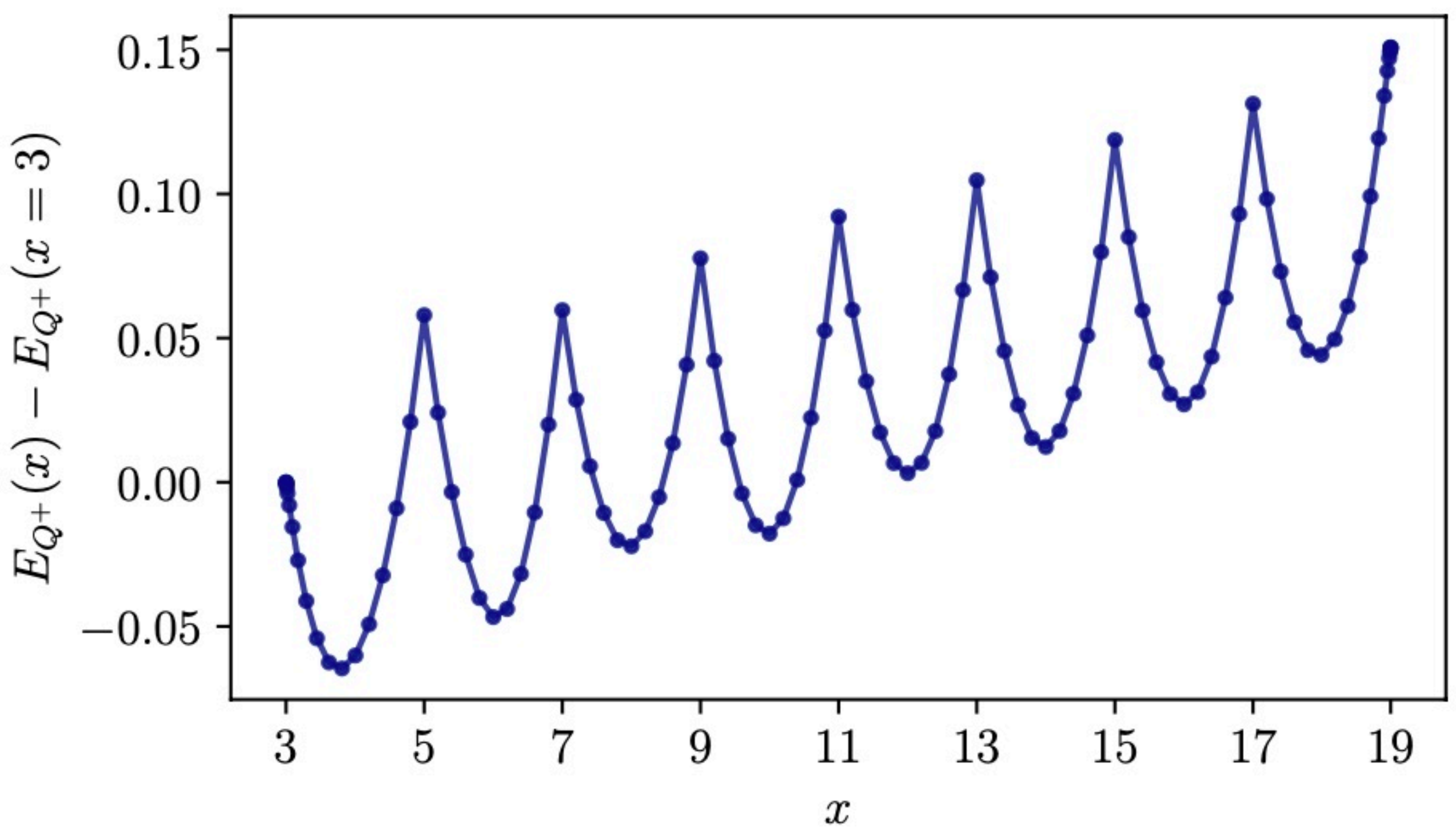


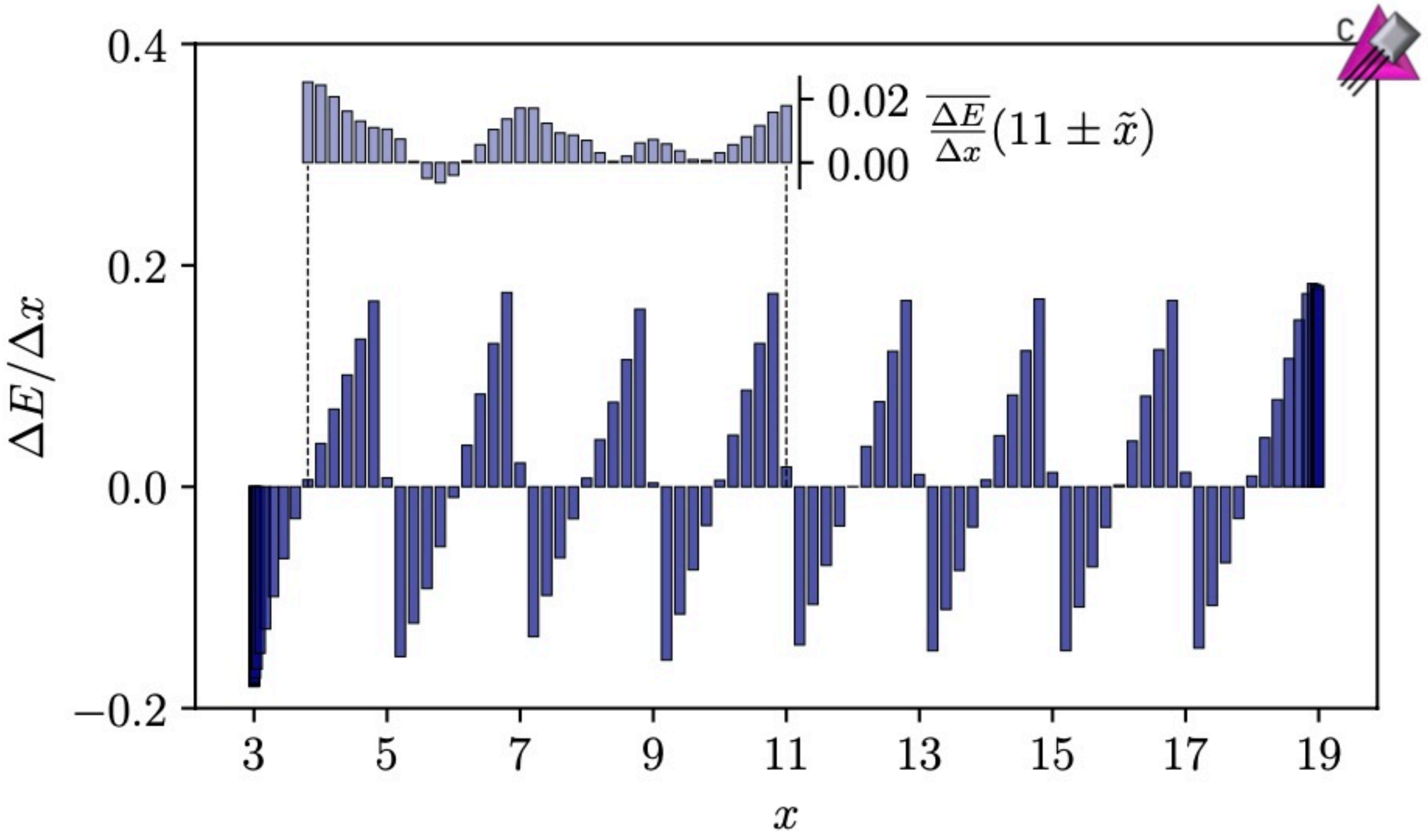
Energy in the Light DOF



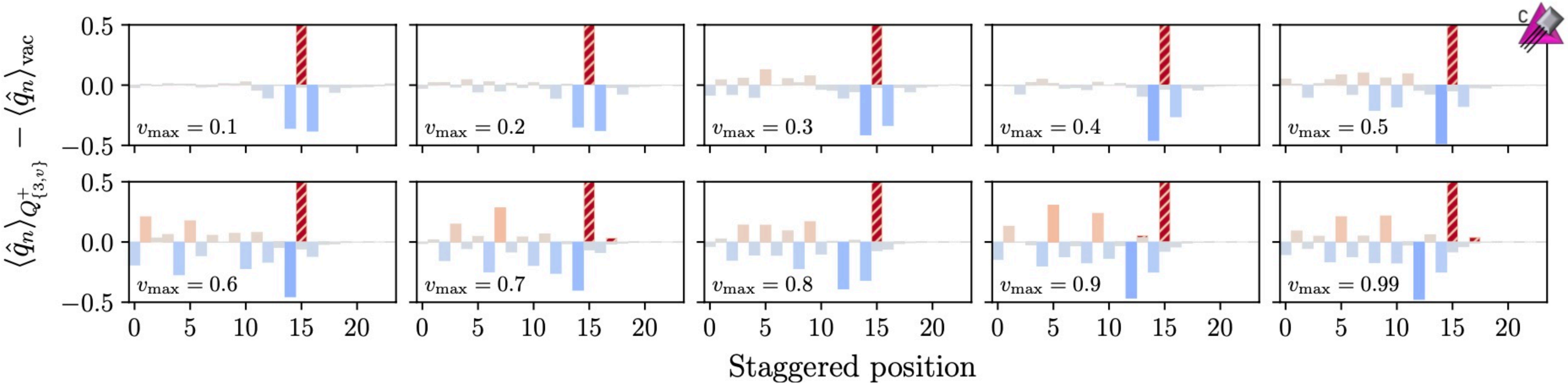
$$E_{Q^+}(x) = \langle\, \psi[t(x)] \mid \hat{H}[t(x)] \mid \psi[t(x)] \,\rangle_{Q^+_{\{x_0,v\}}}$$

$$\frac{dE}{dx}(x) \to \frac{\Delta E}{\Delta x} = \frac{E_{Q^+}(t+\Delta t) - E_{Q^+}(t-\Delta t)}{x(t+\Delta t) - x(t-\Delta t)}$$

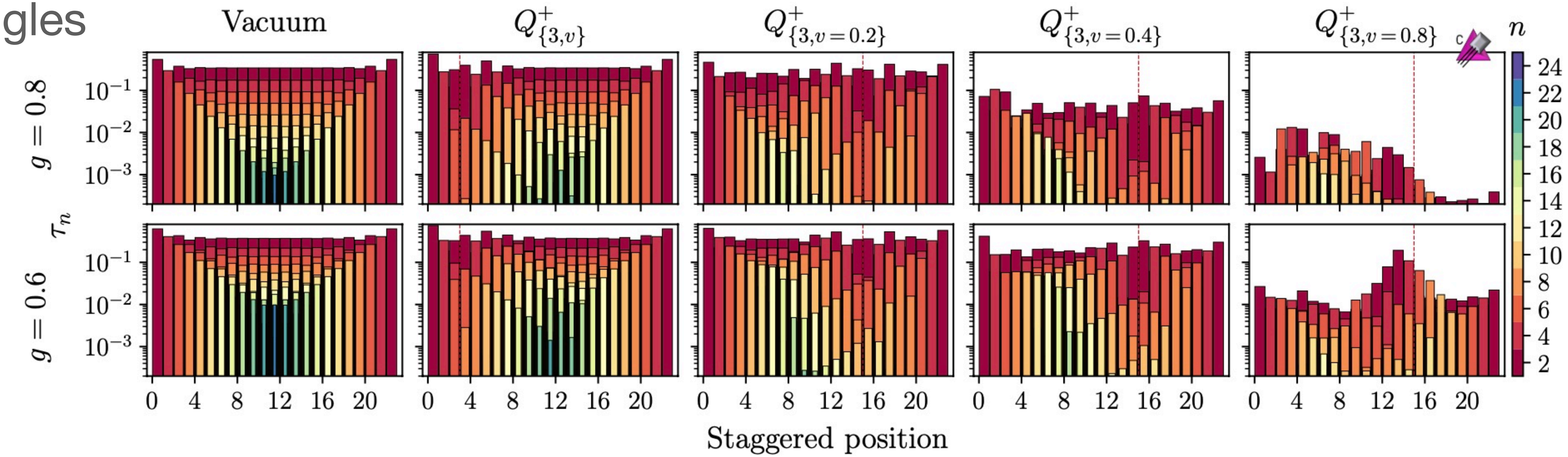




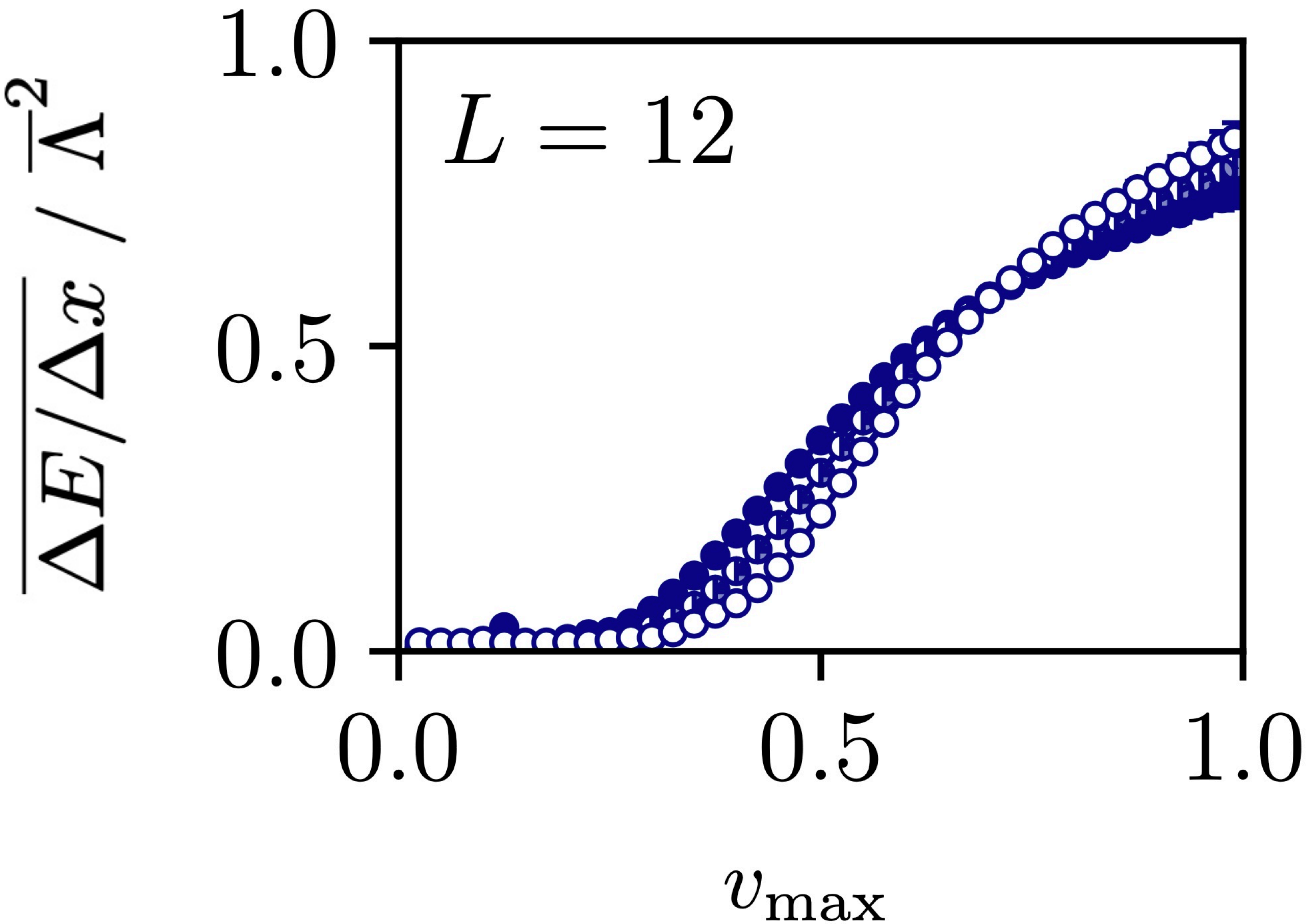
Energy Loss, Hadronization and Damage to Multi-Partite Entanglement in the Vacuum



n-tangles

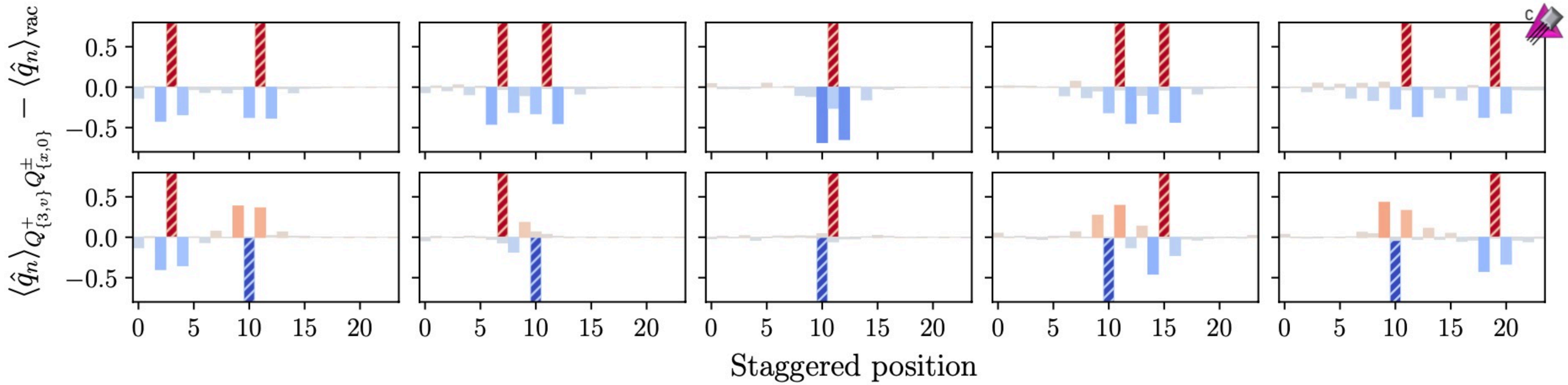


Reducing the Lattice Spacing

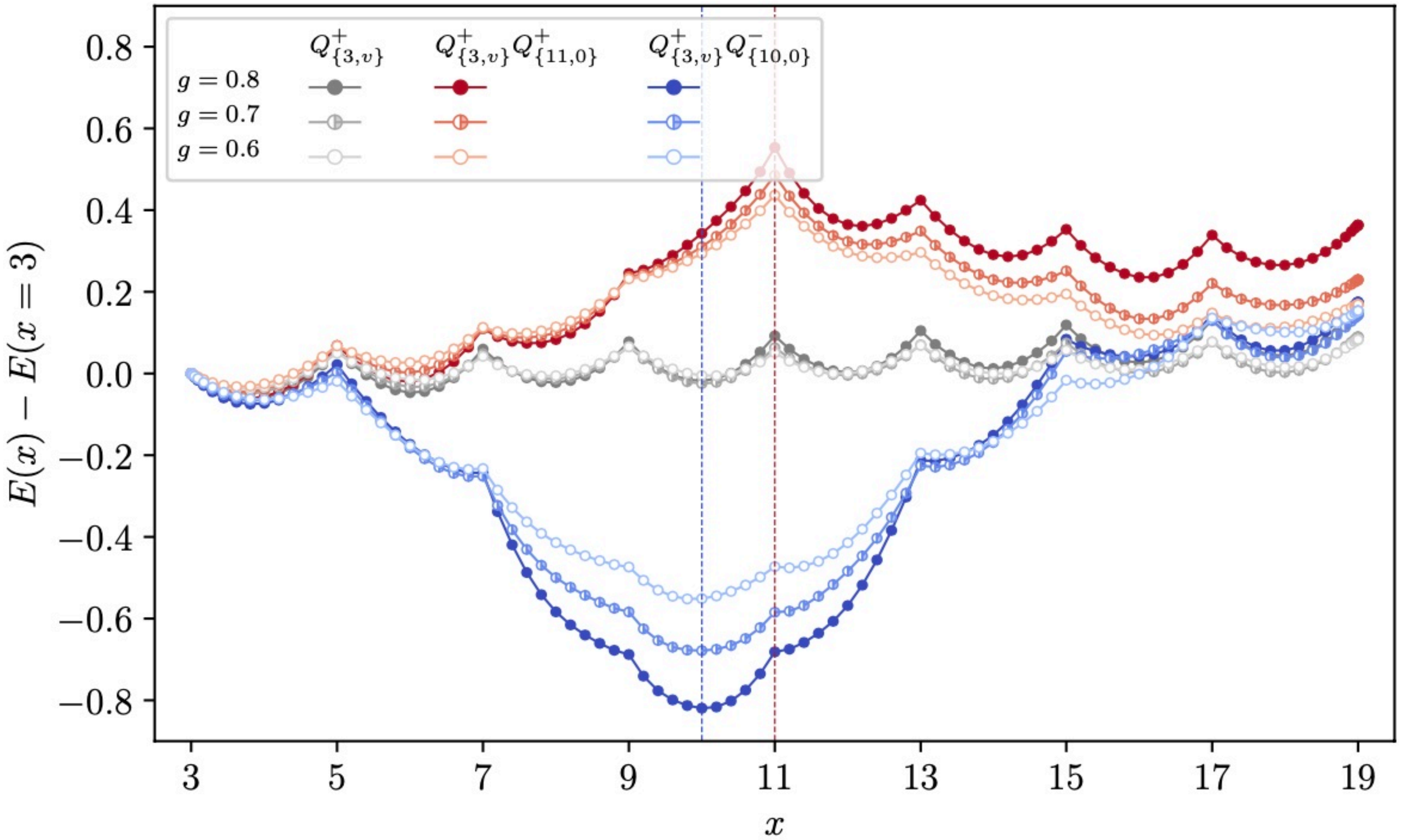


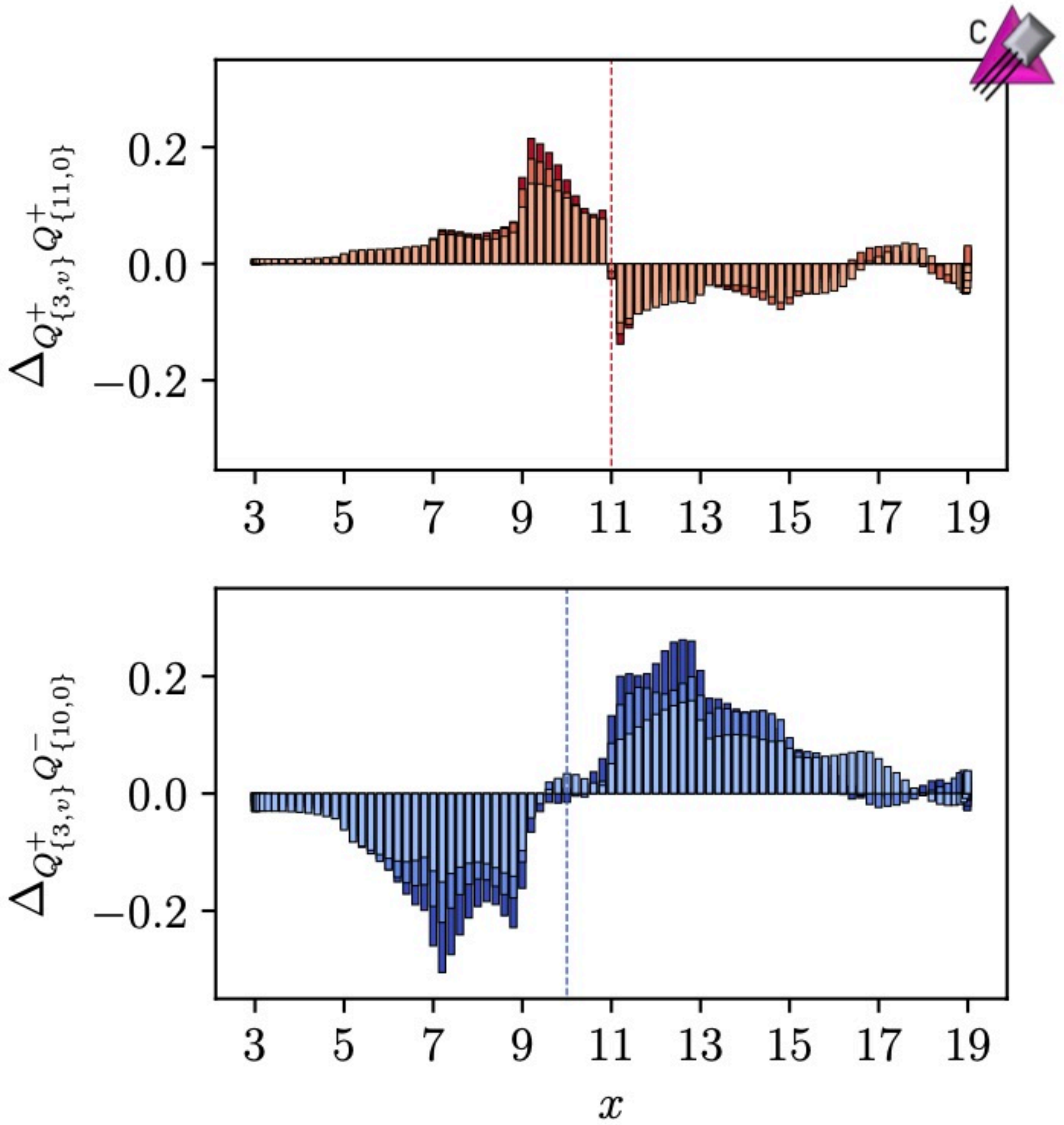
g = 0.8. 0.7, 0.6

Colliding Partons
1 Static Background heavy Quark



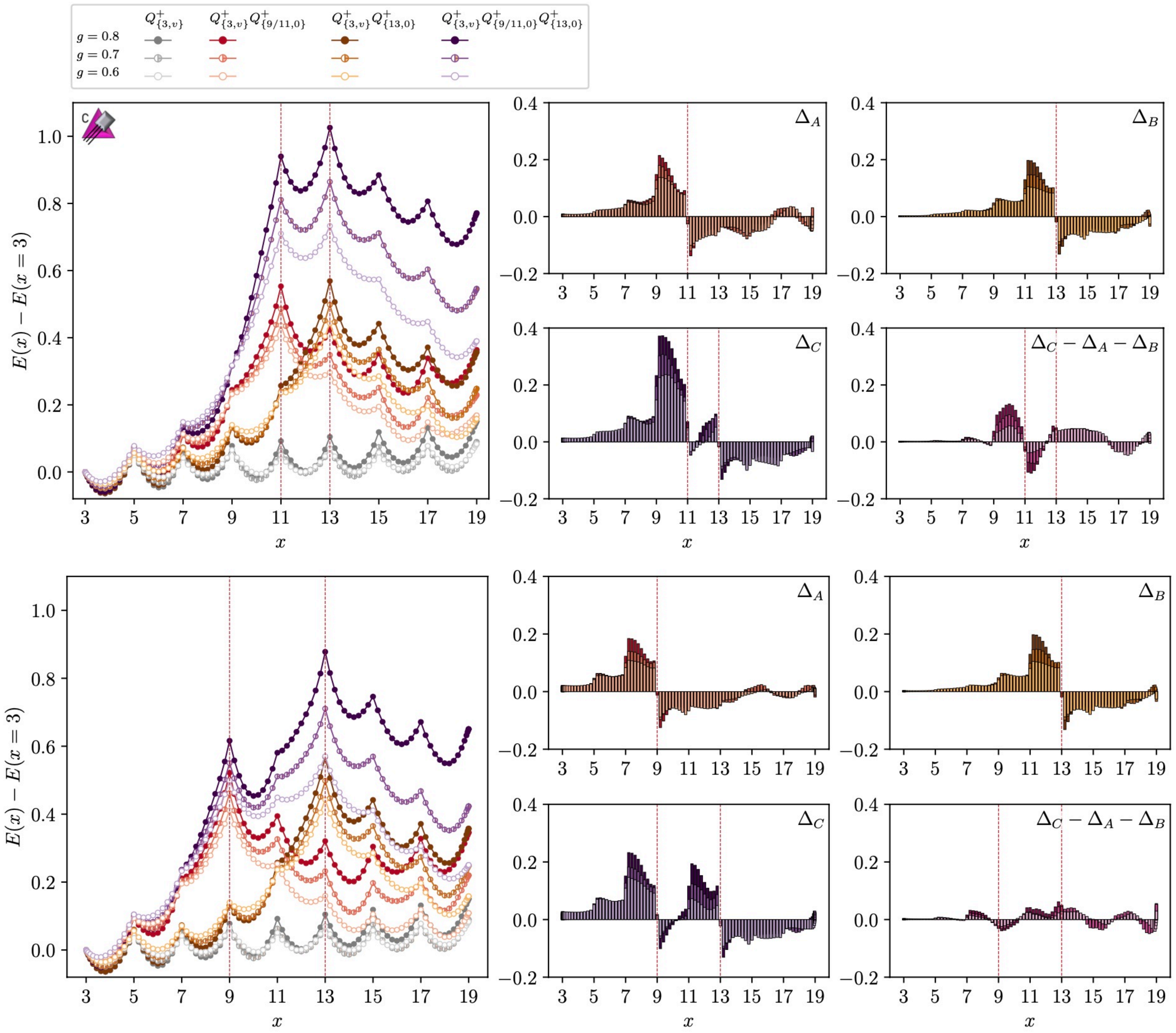
v_{max}=0.2

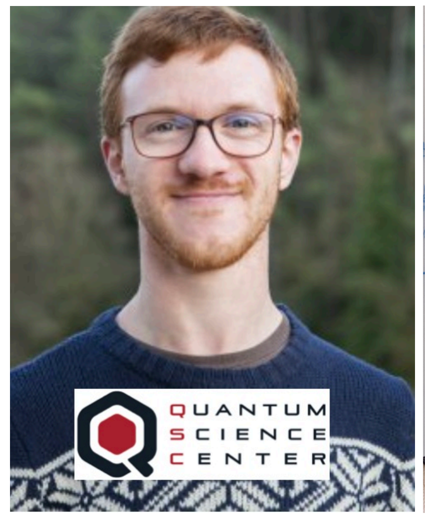


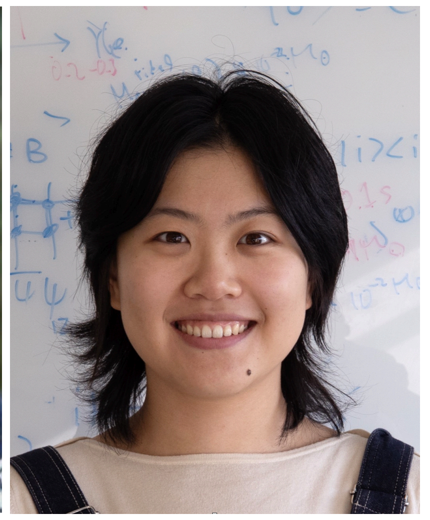


Leading parton collisions dominate energy loss

Matter and Quantum Coherence
2 Static Background heavy Quarks







Framework for Quantum Simulations of Energy-Loss in Non-Abelian Gauge Theories: SU(2) Lattice Gauge Theory in 1+1D

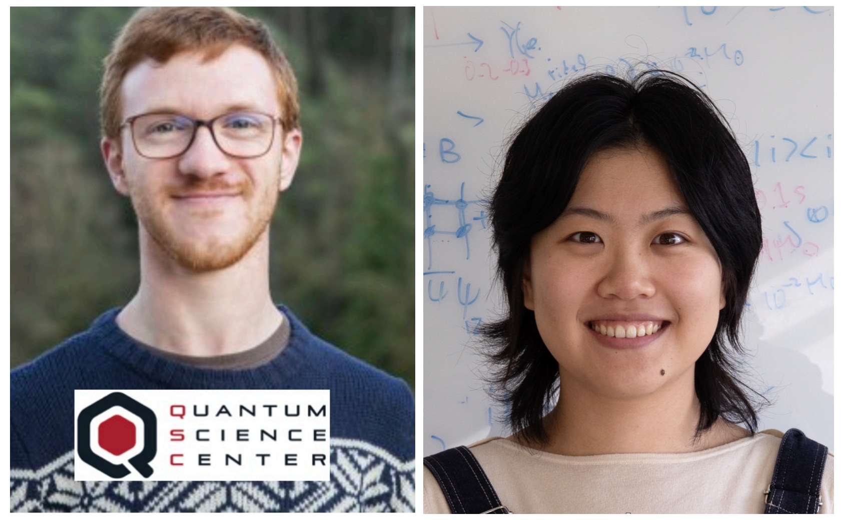
Zhiyao Li[1,*] Marc Illa[1,2,†] and Martin J. Savage[1,‡]

Preprint near completion

SU(2) charges change the wavefunction - Gauss's law implementation not practical

Color neutrality enforced by energy penalty outside of lattice volume

$$|SC; L, 0\rangle = |\downarrow\downarrow\downarrow\downarrow\uparrow\uparrow\rangle^{\otimes L} \qquad |SC; L, 1\rangle = |\downarrow\downarrow\downarrow\downarrow\uparrow\uparrow\rangle^{\otimes k} \frac{1}{\sqrt{2}}\Big[|\downarrow\uparrow\uparrow\downarrow\uparrow\uparrow\rangle - |\uparrow\downarrow\downarrow\uparrow\uparrow\uparrow\rangle\Big] \, |\downarrow\downarrow\downarrow\downarrow\uparrow\uparrow\rangle^{\otimes L-k-1}$$



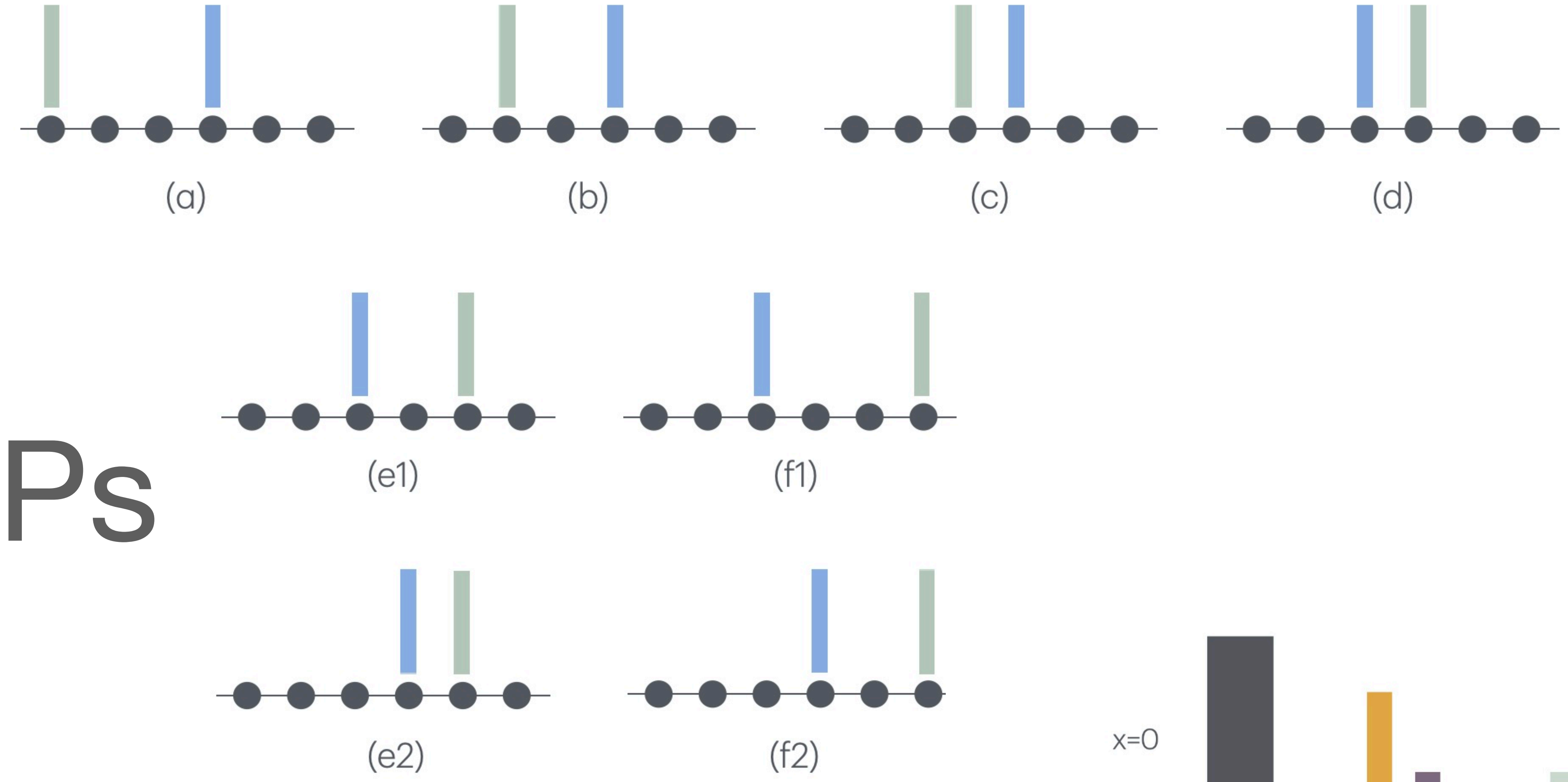
Further Concepts

$$|SC; L, 1\rangle = |\downarrow\downarrow\downarrow\downarrow\uparrow\uparrow\rangle^{\otimes k} \, \frac{1}{\sqrt{2}} \left[|\downarrow\uparrow\uparrow\downarrow\uparrow\uparrow\rangle - |\uparrow\downarrow\downarrow\uparrow\uparrow\uparrow\rangle \right] |\downarrow\downarrow\downarrow\downarrow\uparrow\uparrow\rangle^{\otimes L-k-1}$$

- Color entanglement
  - Hadron interpolating operators

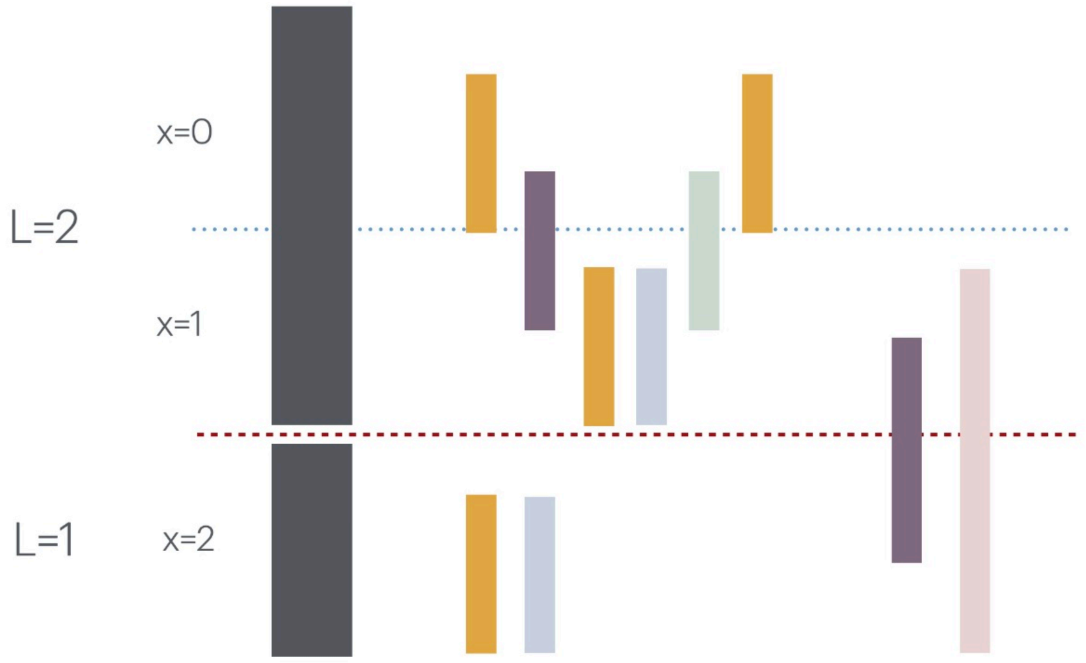
$$\mathrm{FSW\hat{A}P}(\theta) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i\theta/2}\cos\frac{\theta}{2} & -ie^{i\theta/2}\sin\frac{\theta}{2} & 0 \\ 0 & -ie^{i\theta/2}\sin\frac{\theta}{2} & e^{i\theta/2}\cos\frac{\theta}{2} & 0 \\ 0 & 0 & 0 & e^{i\theta} \end{pmatrix}$$

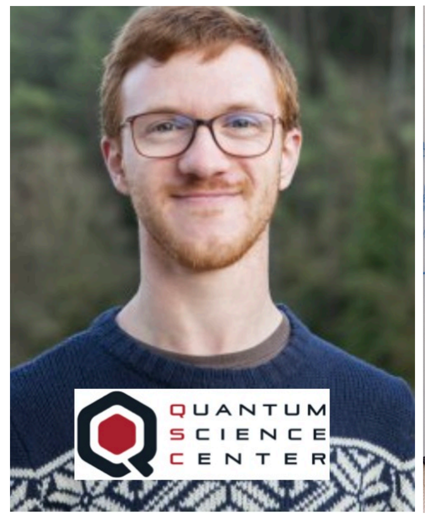
- Heavy-quark motion discrete only
  - by FSWAPs

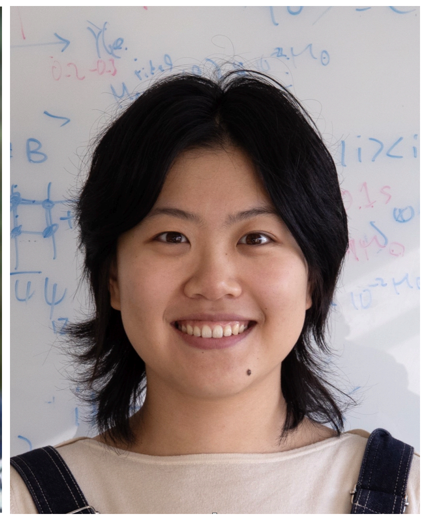


- Lattice spacing artifacts from FSWAPs

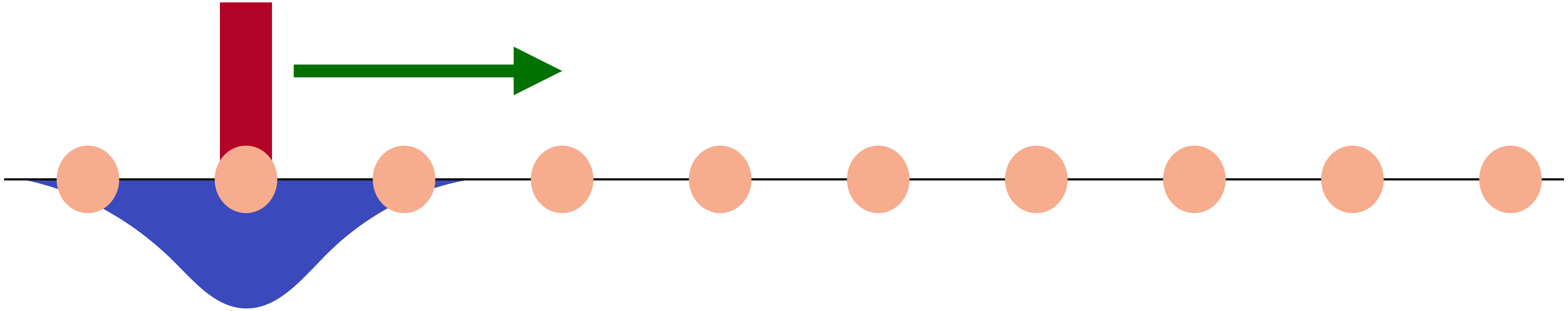
- Domain Decomposition



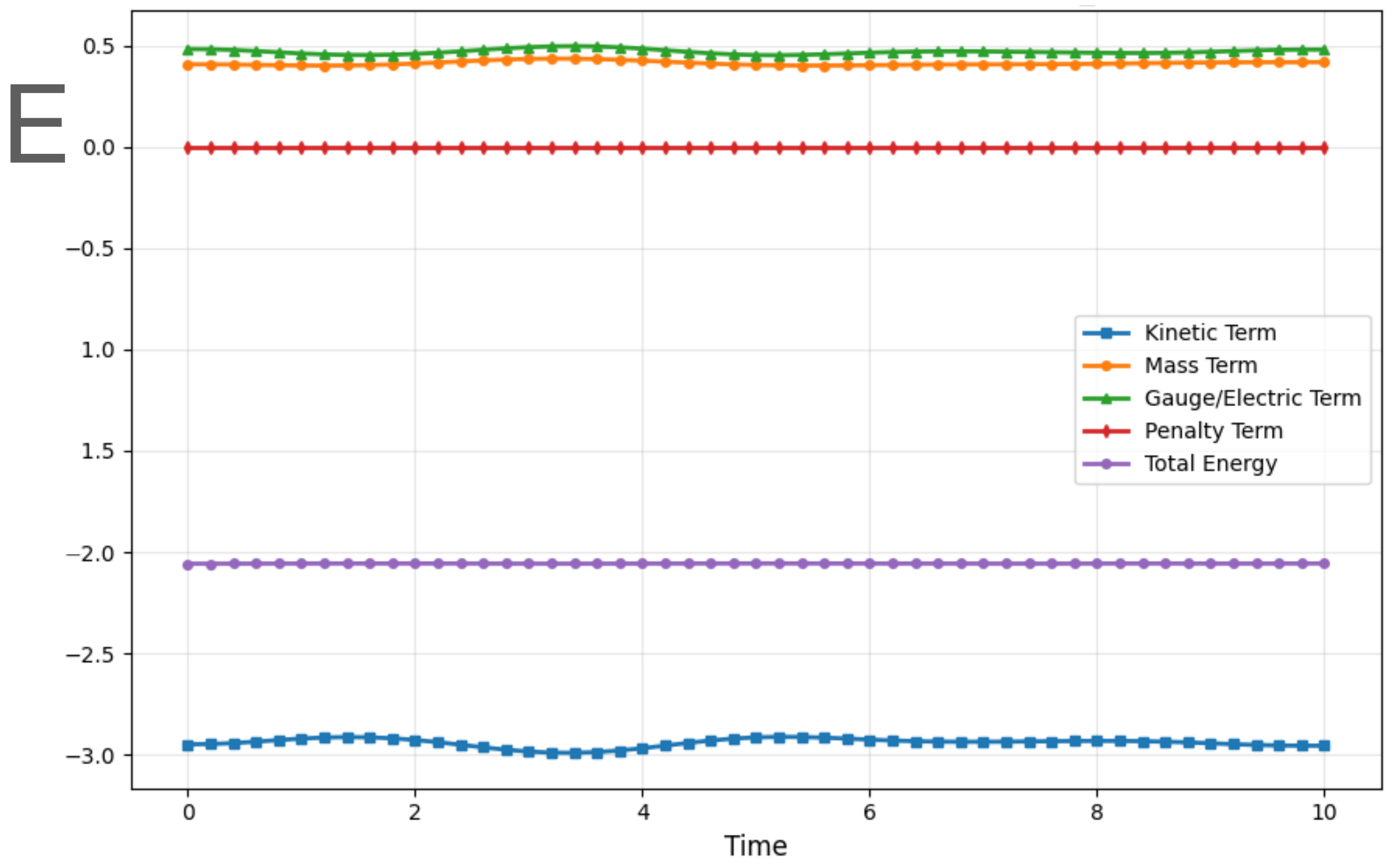


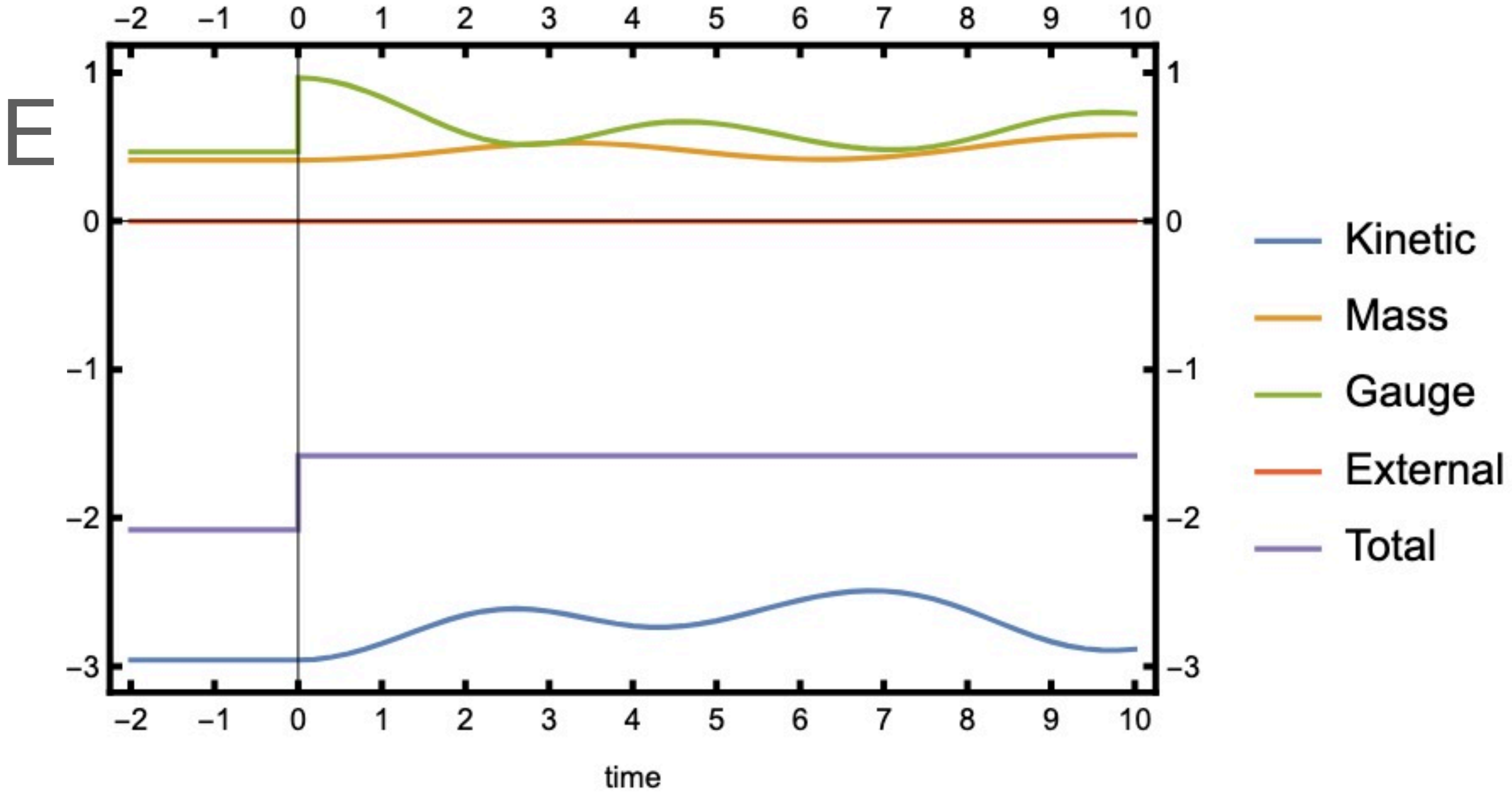


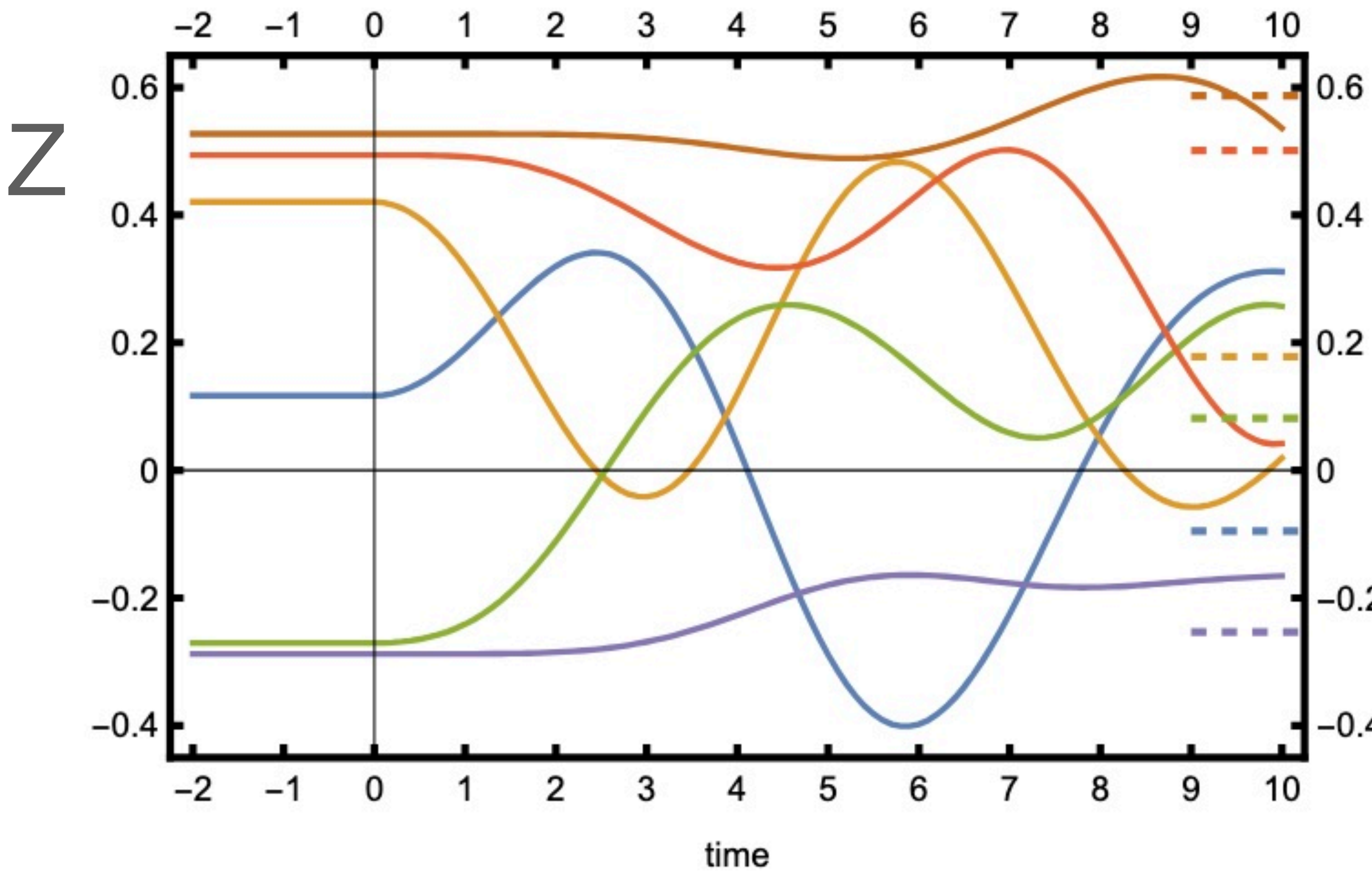
Energy Loss from Real-time Quantum Simulations: SU(2) using Heavy Quarks

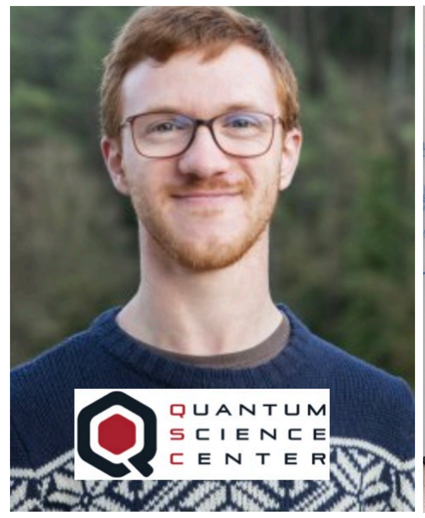
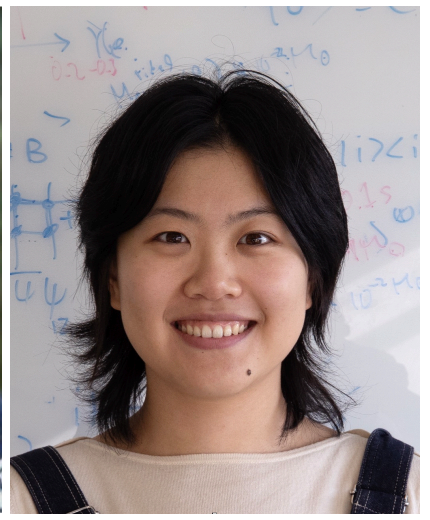


Trotterized ground state heating

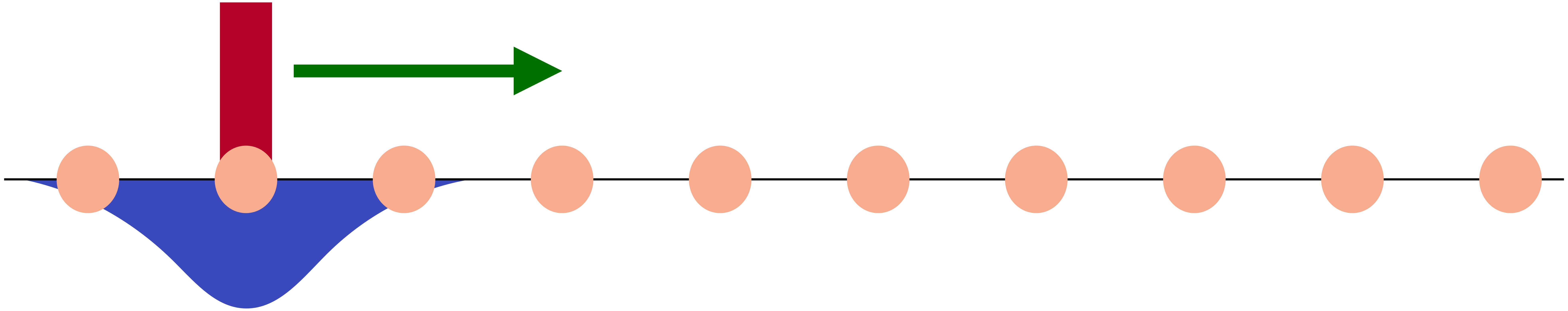




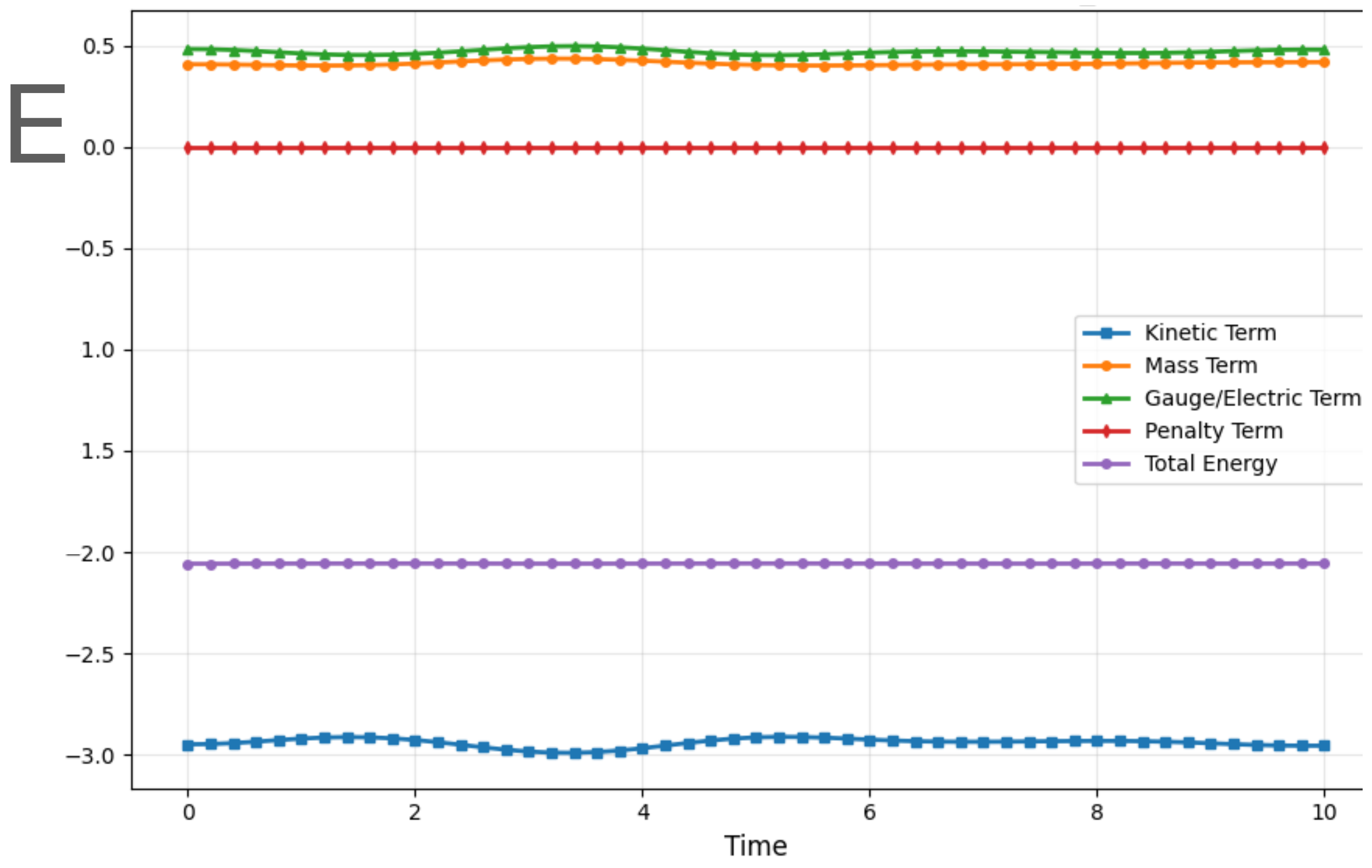


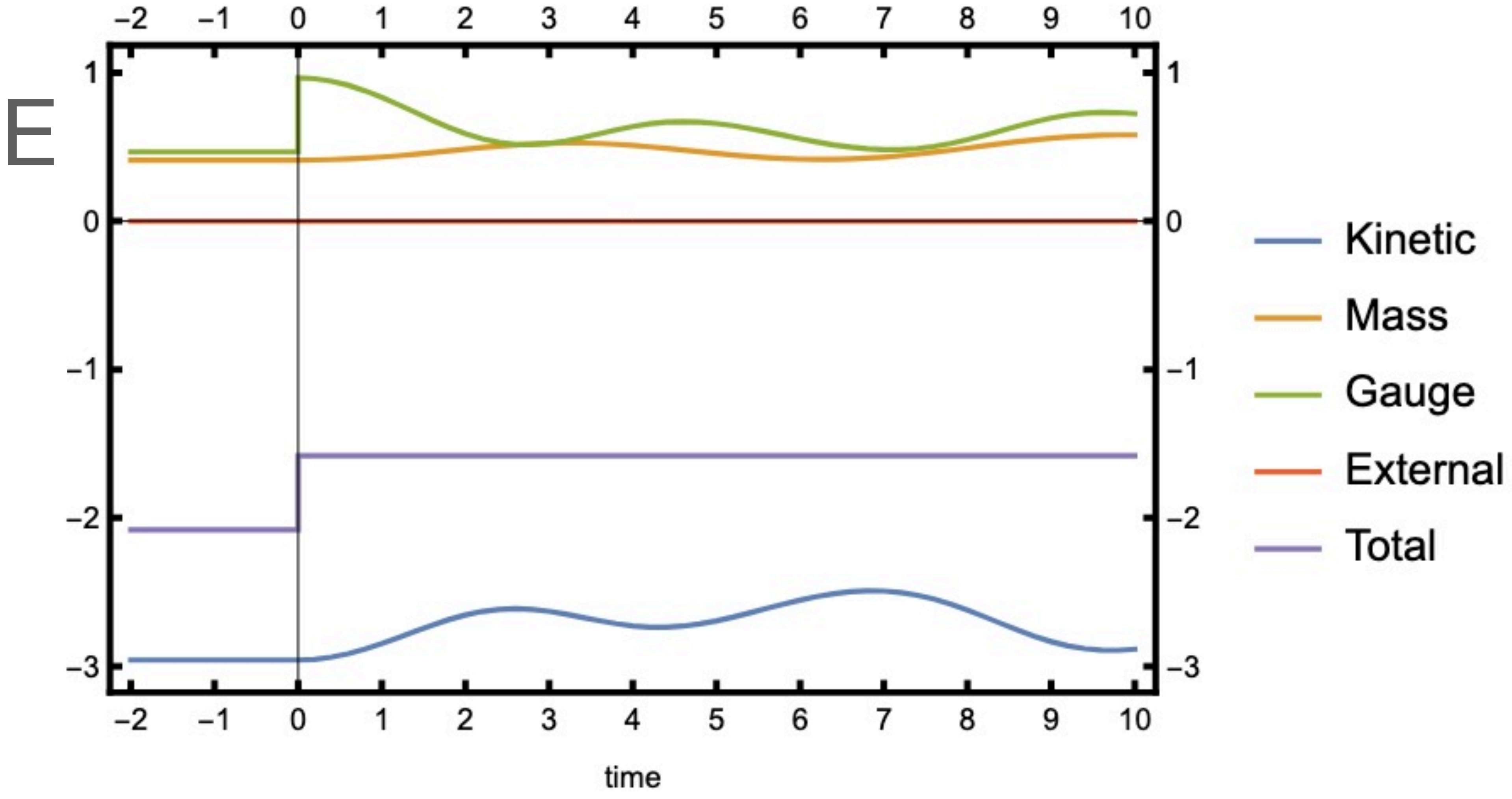



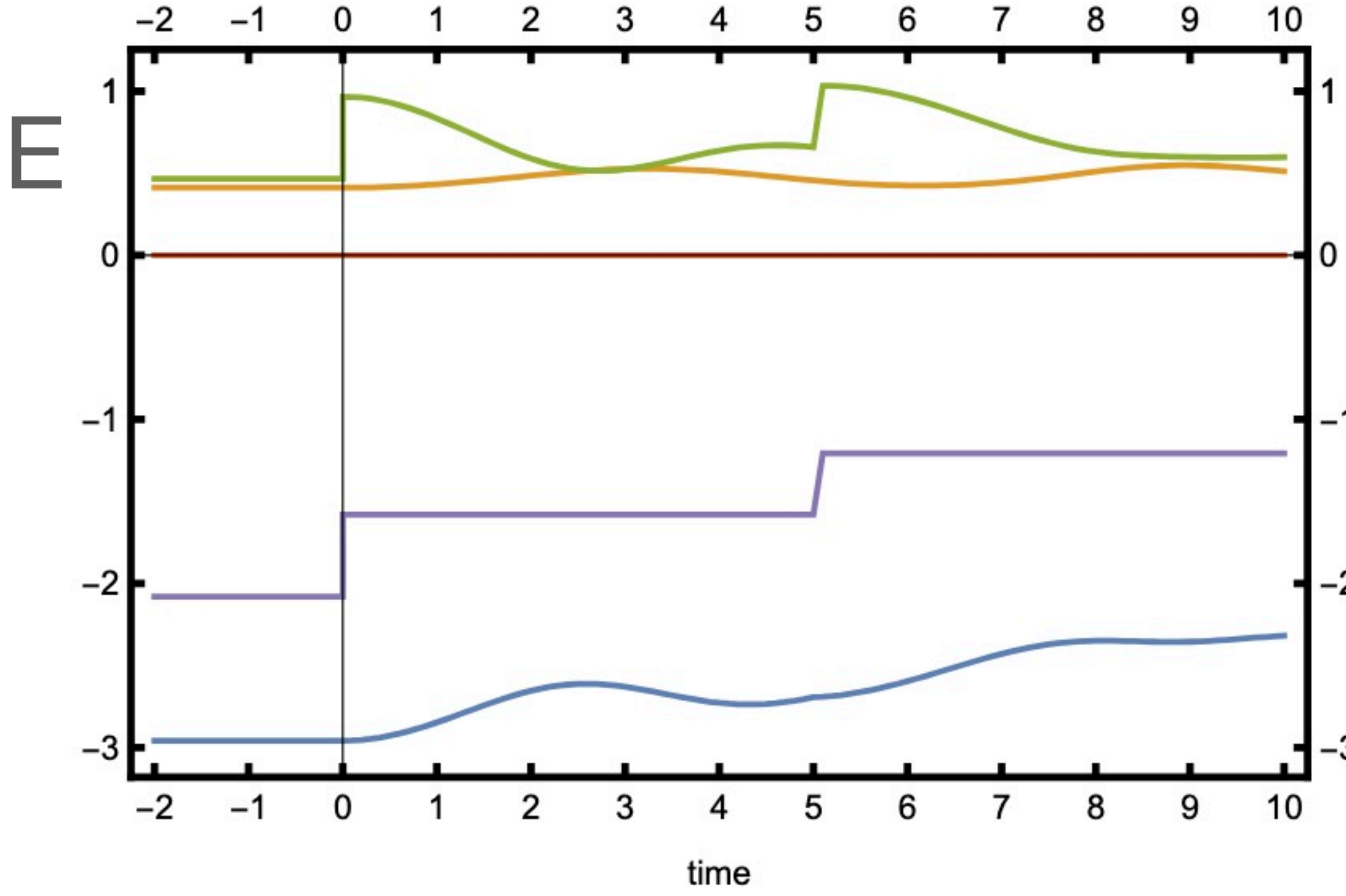
Energy Loss from Real-time Quantum Simulations: SU(2) using Heavy Quarks

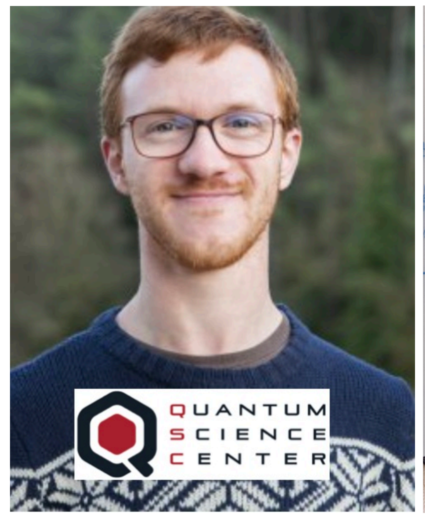


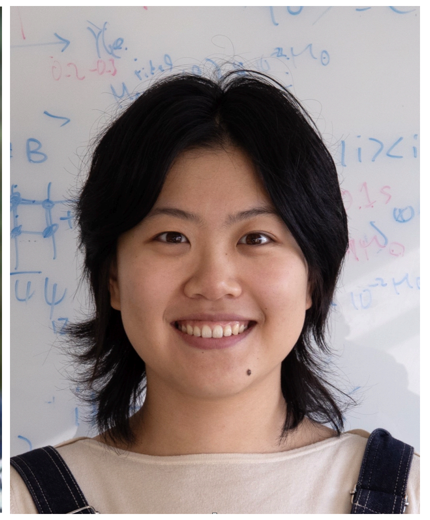
Trotterized ground state heating





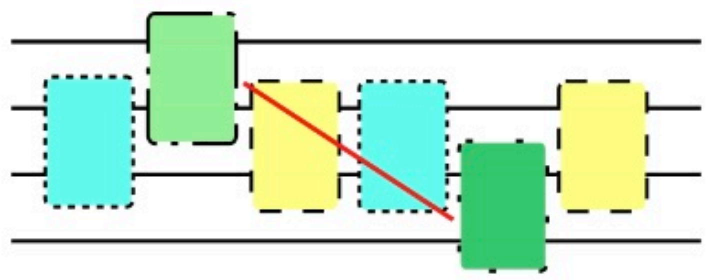




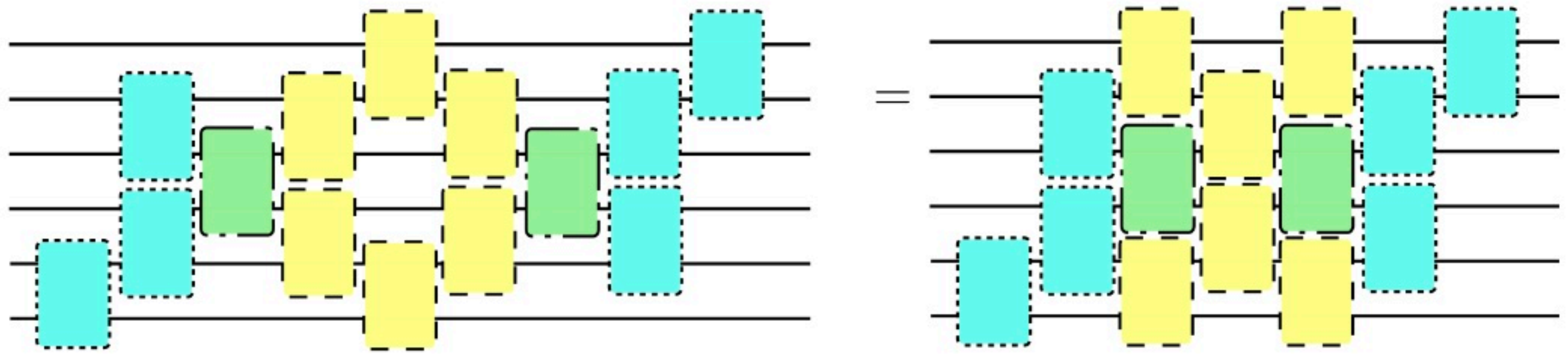


Representative Quantum Circuits for SU(2) State Prep, Motion and Evolution

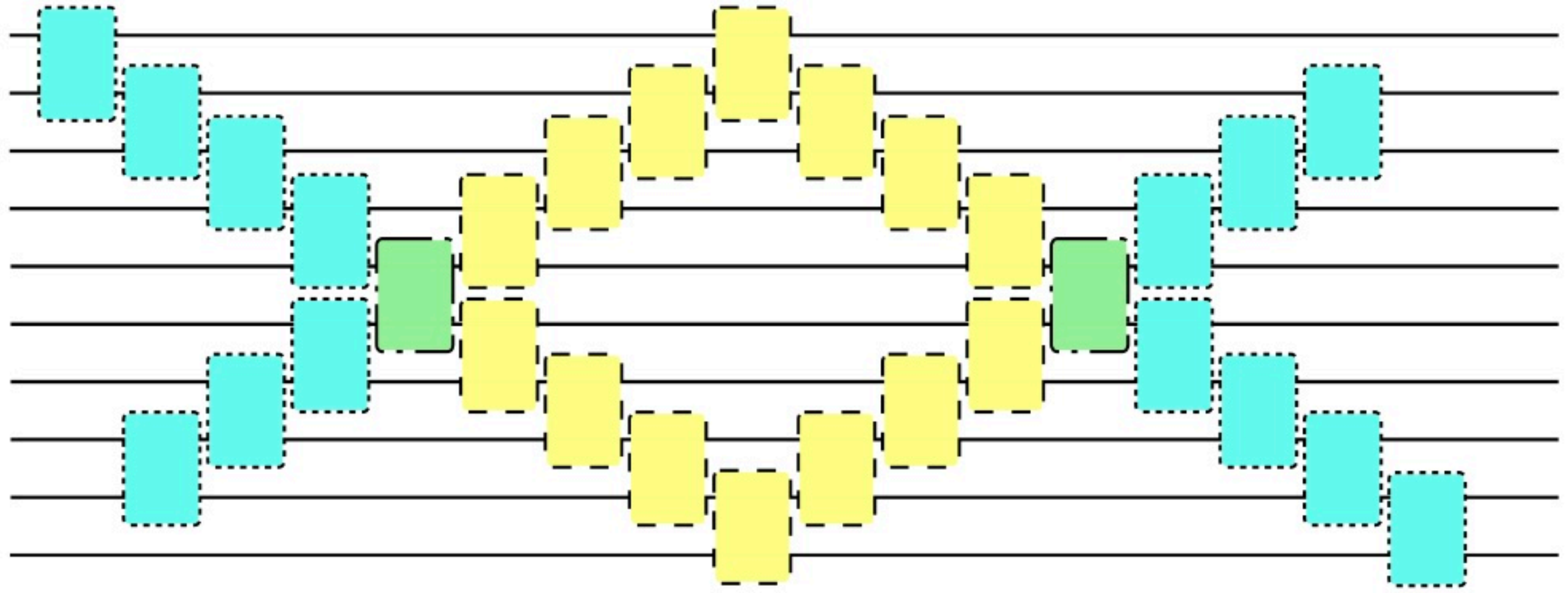
$e^{-i\frac{\theta}{2}\hat{O}_{M0}} =$



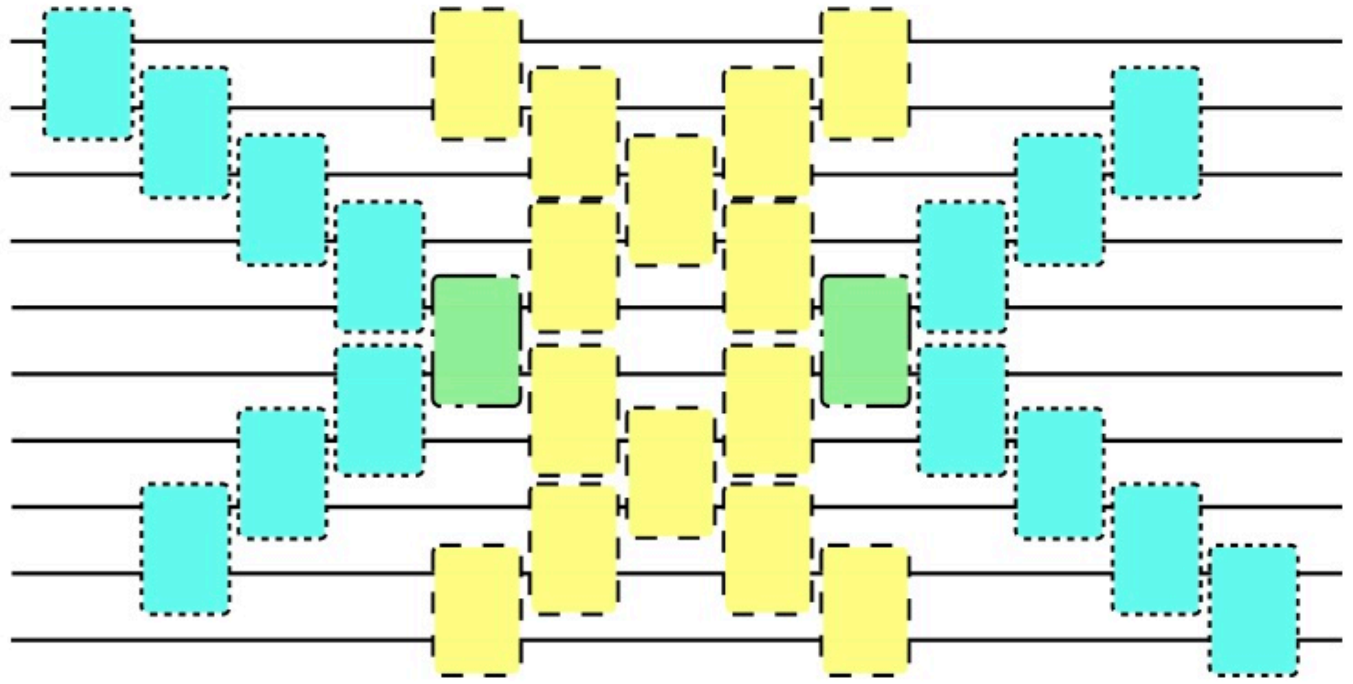
$e^{-i\frac{\theta}{2}\hat{O}_{M1}} =$



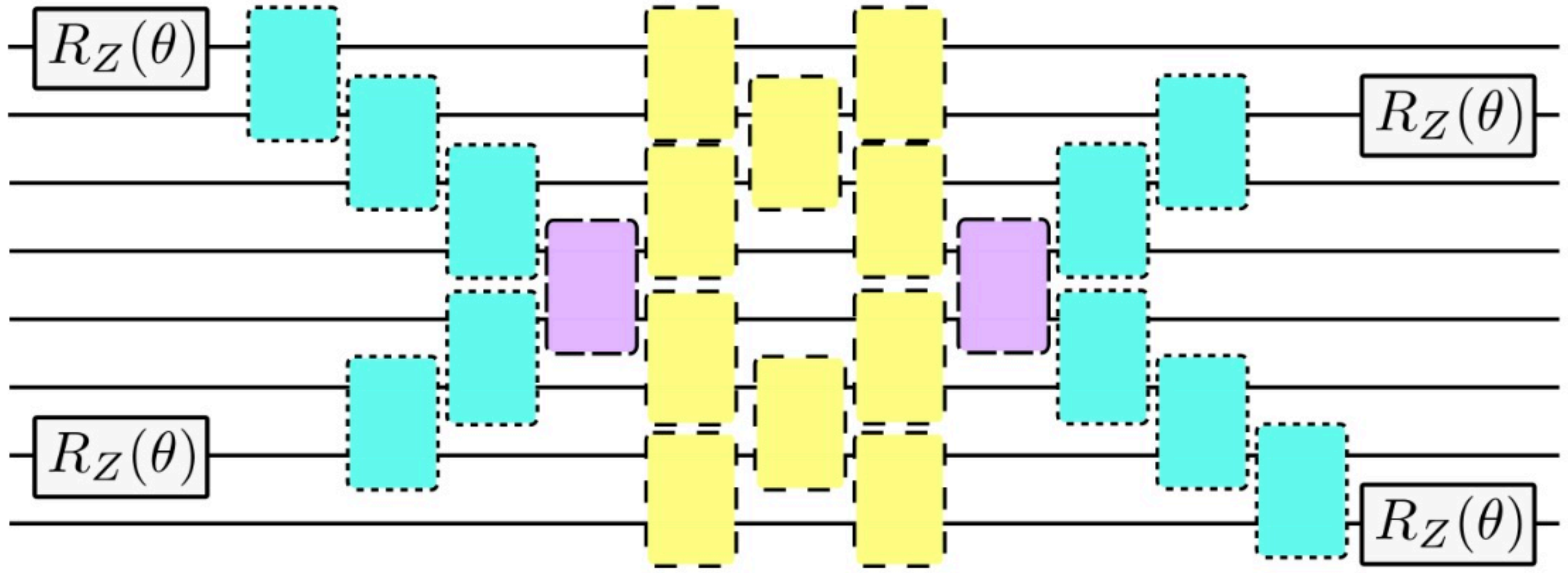
$e^{-i\frac{\theta}{2}\hat{O}_{M2}} =$

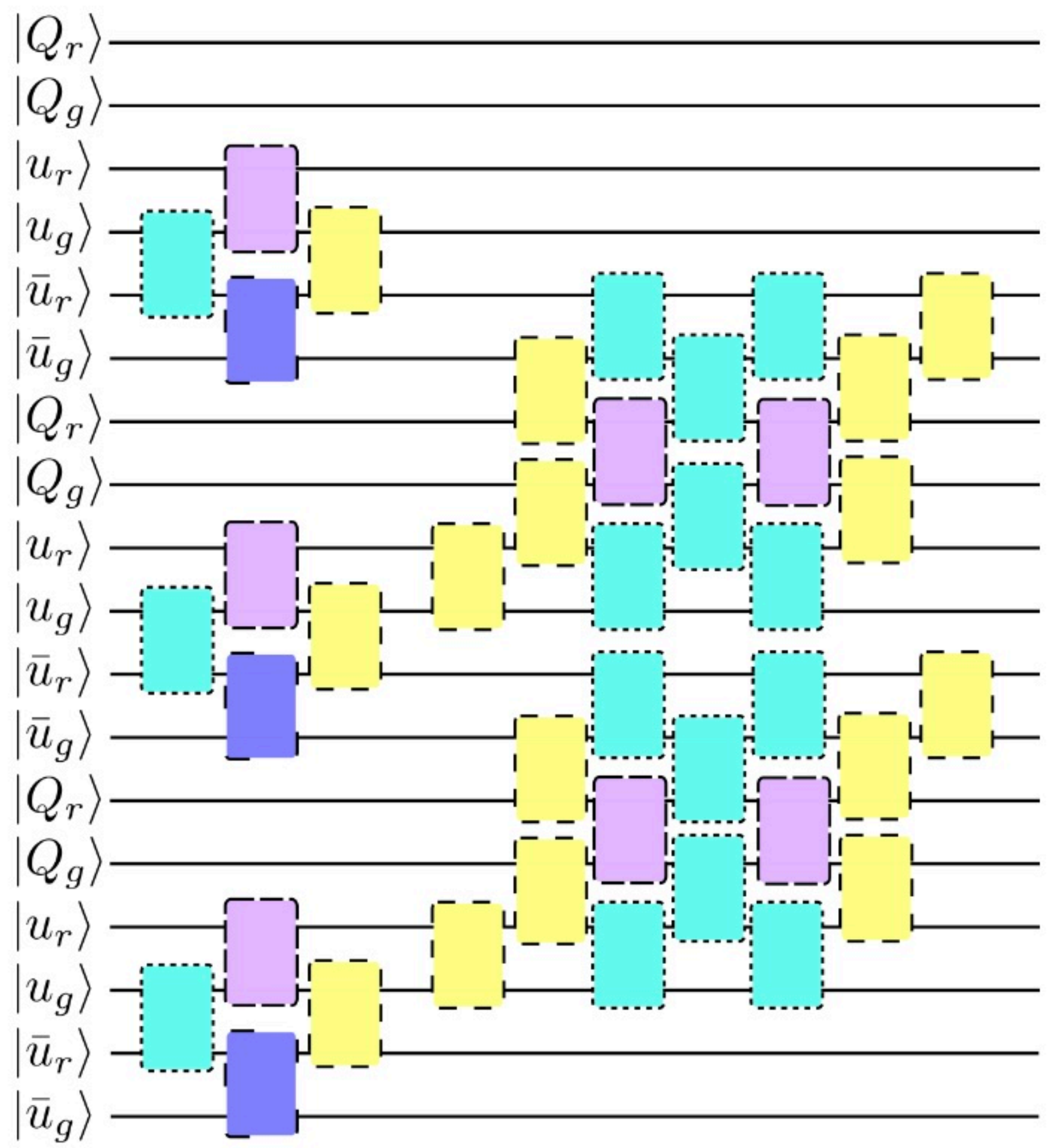


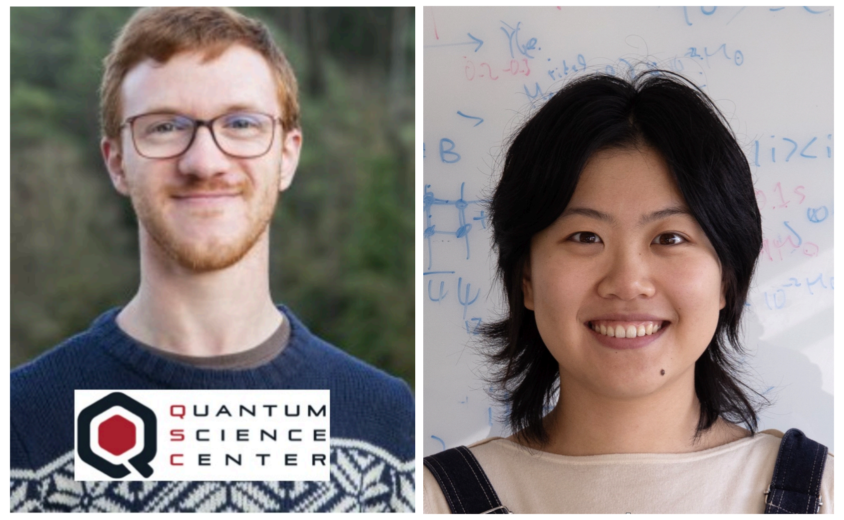
$=$



$\hat{F}_r\hat{F}_g =$



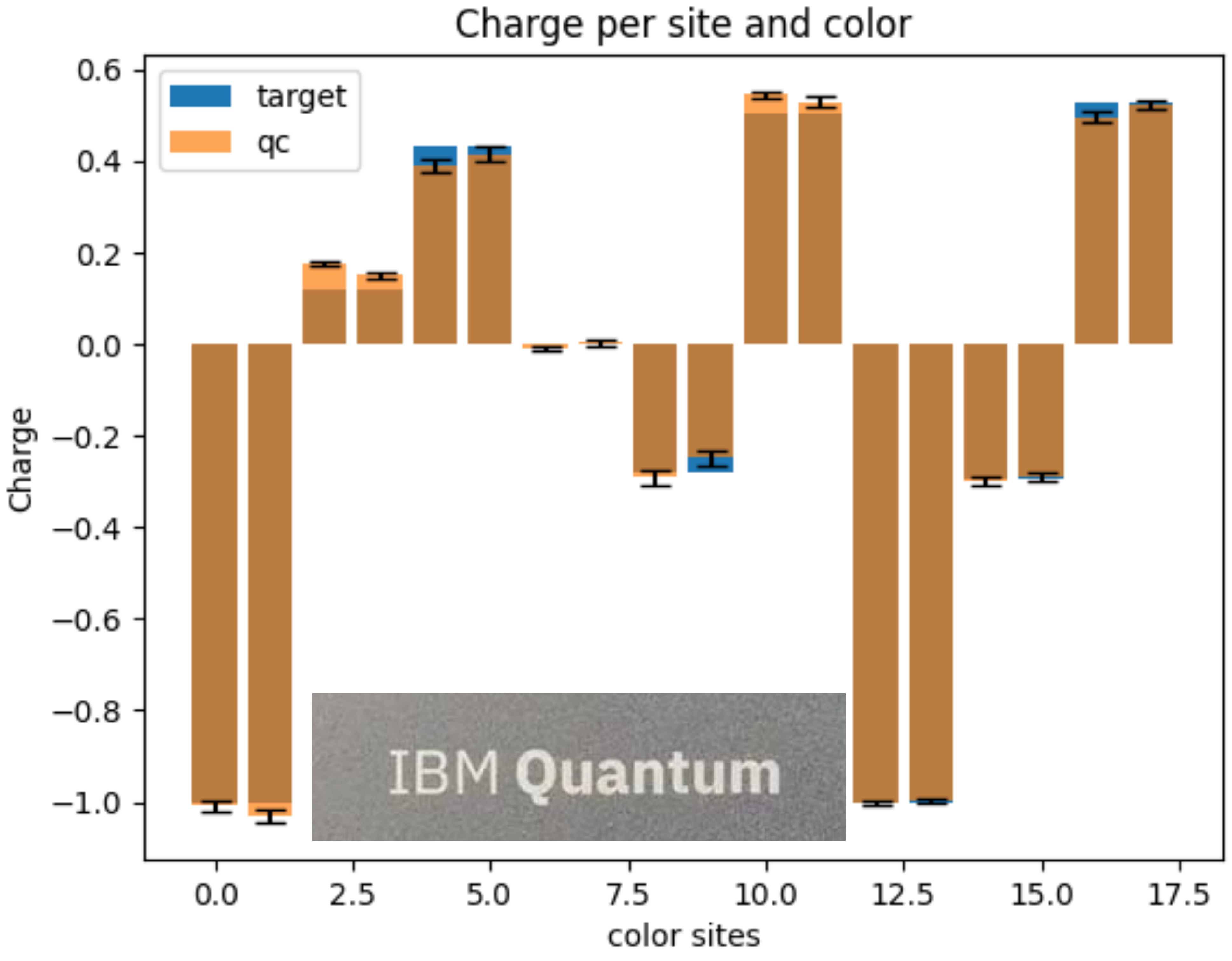




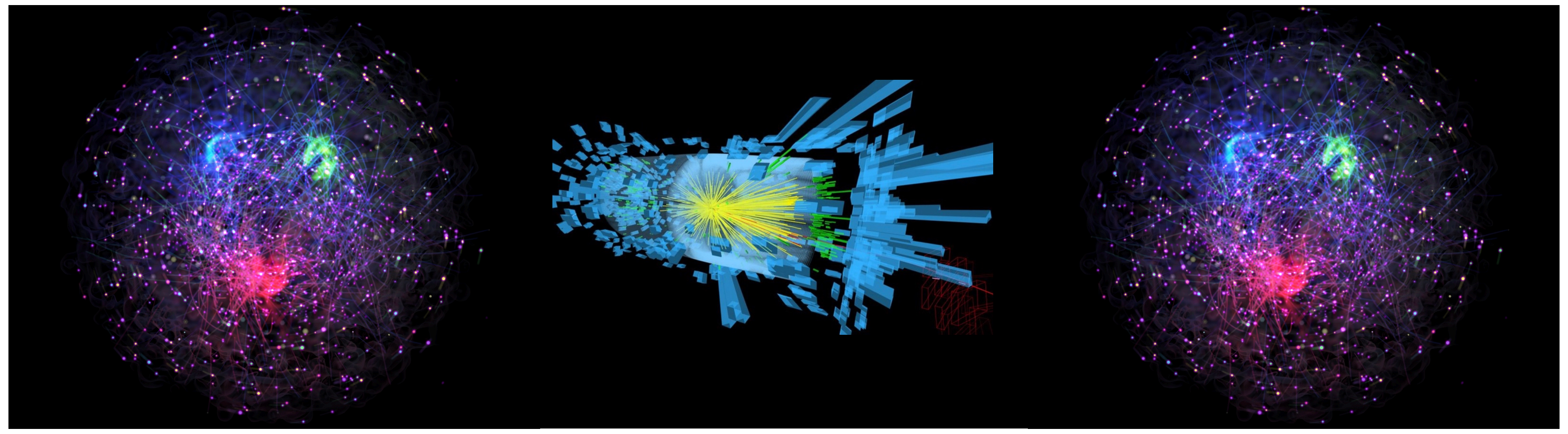
Results from IBM Torino

Transpired Gate Counts for State Prep and One Trotter Step

```
4517 gates: OrderedDict({'sx': 1957, 'rz': 1452, 'cz': 1004, 'x': 104})
Depth: 1350
Two-qubit gate depth: 456
```



The Future



1+1D U(1), SU(2) and SU(3)

Quantum simulations with larger systems and reduced uncertainties

IQuS

2+1D

Extend 1+1D frameworks - dynamical gauge fields, peripheral collisions, etc

Systematic error quantification

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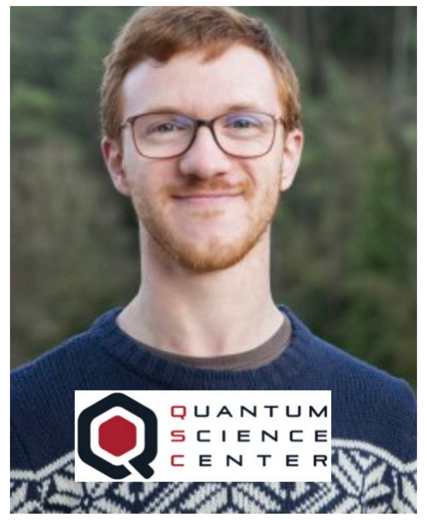

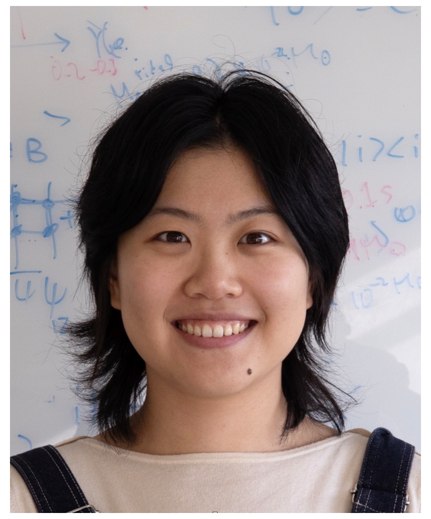

Roland Farrell

Marc Illa

Zhiyao Li

Office of Science
U.S. Department of Energy

Oak Ridge National Laboratory

FIN